Study of soil-tine interaction for the application of automated mechanical weeder

Safal Kshetri
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Study of soil-tine interaction for the application of automated mechanical weeder

by

Safal Kshetri

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural and Biosystems Engineering

Program of Study Committee:
Brian L. Steward, Major Professor
   Stuart Birrell
   Mehari Tekeste
   Lie Tang
   Kris De Brabanter

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2020

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Mechanical cultivation is common weed control method for organic farming. A wide variety of mechanical tool designs exist for mechanical cultivation applicable for inter-row and intra-row weeds. Some of the tool designs for intra-row weeding require active control in the row and sometimes between the rows. For these tools, the knowledge of soil disturbance and forces at different operational settings could help achieve desired weeding performance from the tools. Information on soil disturbance could help when making operational decision that focus on damaging weeds without harming the crops. Understanding soil reaction forces on a weeding tool could be valuable for achieving desired movement of the tool required for higher weeding efficacy. Soil disturbance and forces are two important aspects which could be explored using soil-tool interaction study to optimize settings and design of a weeding tool to achieve higher weed control. In this research, interactions between soil and tines of an intra-row weeder prototype were investigated for effective weeding. The prototype consisted of vertical rotating tines for weeding which were intended to move in and out of the crop row by an actuator.

The first objective of this research was to develop a method to investigate the effects of soil and tool interaction on weeding performance for different settings in a controlled environment. Specifically, the effects of tines on small wooden cylinders, used as simulated weeds, were investigated through soil disturbance at different settings. Experiments for the study were conducted using a single cylindrical tine and a rotating tine mechanism in a loam soil. The total width of the soil disturbance and potential weeding rate were evaluated for the single cylindrical tine at different tine diameters (6.35 mm, 7.94 mm and 9.53 mm), working soil depths (25.4 mm, 50.8 mm and 76.2 mm) and two tine speeds (0.23 m/s and 0.45 m/s). The width of soil disturbance increased with increasing test levels of depth and diameters, while there was no
significant evidence that tine speeds affected the width of soil disturbance. Potential weeding rate for a single tine was found to be affected by tine diameter, working depths and tine speeds. Particularly, the potential weeding rates increased with increasing levels of the three parameters.

For the rotating tine mechanism, potential weeding rate was analyzed at different working soil depths (25.4 mm and 76.2 mm) and rotational speeds (25, 50 and 100 rpm). The potential weeding rate for the mechanism was found to increase for higher levels of working soil depths and rotational speeds. A simulation was developed to estimate area of soil disturbance caused by rotating tine mechanism at the same settings used in the experiment for the mechanism. The simulation results showed the percentage of disturbed soil area matched the patterns of the percentage of disturbed simulated weeds in the experiment.

For the second objective of the research, models were developed to estimate soil forces on a vertical tine of a rotating tine mechanism operating at different linear and rotational velocities. Separate models were developed for longitudinal and tangential forces which relate to horizontal draft force and torque on the tine, respectively. The models used longitudinal velocity and speed ratio as kinematic parameters associated with linear and rotational velocities. Longitudinal velocity was the forward traveling velocity of the rotating tine mechanism across the soil bin length. Speed ratio was the ratio of longitudinal velocity to peripheral velocity of the tines due to rotation of the mechanism. The models also accounted for shearing and inertial forces on the tine and associated coefficients were acquired empirically. Two sets of soil bin experiments were conducted using artificial soil: (i) with one tine to estimate the coefficient values and (ii) with two tines 180° apart to evaluate model performance. A working soil depth of 70 mm and tine diameter of 6.35 mm were used for both experiments. In the experiments, horizontal draft force and torque were measured across variation of two experimental factors:
longitudinal velocity and speed ratio. Three levels of longitudinal velocity were 0.09 m/s, 0.29 m/s and 0.5 m/s, and three levels of speed ratio were 1, 1.5 and 2. The coefficients estimated by curve fitting experimental data using nonlinear least squares method yielded values of $K_S$ ranging from 2.96 to 37.5 N and $K_I$ ranging from 16.6 to 528 N·s²·m⁻² for the treatments. The different values of the coefficients captured the variation in shearing and inertial forces on the tine due to difference in patterns of soil failure among the treatments. The means of longitudinal and tangential forces predicted using the model for two tines 180° apart had trends similar to those of means of respective measured forces for different treatments. However, the model underestimated the predicted forces because it did not account for the reduced force on a tine due to soil disturbance created by the other tine.

In the research, the third objective was to study the effects of linear and rotational velocities on horizontal draft force and torque on the rotating tine mechanism operating in the soil. Experiments were conducted using the rotating tine mechanism consisting of four vertical cylindrical tines 6.35 mm in diameter in a soil bin with loam soil. The working soil depth of 70 mm was used throughout the experiment, and draft force and torque were investigated across different levels of longitudinal velocity and speed ratio. In the study, three levels of longitudinal velocity (0.09 m/s, 0.29 m/s, 0.5 m/s) were used for both draft force and torque. Four levels of the speed ratio (0, 1, 1.5 and 2) were used for investigating draft force and torque. Analysis of Variance (ANOVA) was conducted using significance level of 5%. The result showed the draft force, in general, decreased with increasing levels of speed ratio for the three levels of longitudinal velocity. The torque for different longitudinal velocity was found to increase, for most cases, as the speed ratio increased. These relationships were non-linear and exhibited large variability likely due to complex physical process that occurred during dynamic interaction
between soil aggregates and tines of the mechanism. The results suggest that linear travel and rotational velocities can be optimized to manipulate draft force and torque of the rotating tine mechanism while targeting for desired weeding performance.
CHAPTER 1. GENERAL INTRODUCTION

Weed plants growing close to the crop or vegetable plants decrease their yield and quality by competing for available resources such as nutrients, water and sunlight (Slaughter et al., 2008, Van der Weide et al., 2008). Therefore, weed control is a very important activity in agriculture. There are several methods of weed control such as manual weeding, and chemical, biological, thermal and mechanical weed control approaches.

Among these methods, chemical and mechanical weeding are currently the most relied upon techniques in conventional cropping systems (Young et al., 2014). Chemical weeding, which involves the use of herbicide to kill weeds, may be the most economically and biologically effective way to control weed; however, growing concern towards its impact on the environment and increasing consumers demand for organic foods have resulted in some shift of attention towards mechanical weed control (Griepentrog et al., 2006; Slaughter et al., 2008; Young et al., 2014).

Mechanical weeding involves the use of mechanisms to control weeds using three main physical techniques: burying, cutting, and uprooting (Ahmad et al., 2014). Cutting kills weeds by shearing them off. Burying impedes growth of weeds by covering them with a layer of soil. Uprooting dislodges weeds from soil, thus depriving them of nutrients and resources required for further development. Mechanical weeding has been divided into two weeding strategies based on the spatial relationship between crop plants and weed plants: (1) inter-row weeding and (2) intra-row weeding (Ahmad et al., 2014). Inter-row weeding is a weeding method performed between the crop rows, while intra-row weeding is done between the plants within a crop row. Intra-row weeding is more difficult to implement compared to inter-row weeding because it requires control of weed plants growing close to the crops in a row. To overcome the challenge associated
with intra-row weeding, research efforts have increased in the development of effective intra-row weeding systems (Perez-Ruiz et al., 2012). Additionally, research can also be found focusing on the development of automatic or robotic intra-row weeders (Melander et al., 2015; Astrand & Baerveldt, 2002; Griepentrog et al., 2006).

Slaughter et al. (2008) organized robotic or automated weeding research into four core technologies that are identified for autonomous weed control systems: (a) vehicle guidance, (b) plant detection and identification, (c) precision-in-row weed control, and (d) mapping. Vehicle guidance enables accurate positioning of the autonomous vehicle or weeding system required for weeding. Plant detection and identification is required to separate weed plants from crop plants. After separating crops and weeds, intra-row weeding mechanisms (for mechanical weeding) or spray nozzles (for chemical weed control) are controlled to precisely target the weed plants and damage their structure disrupting their growth or killing them. Mapping is a technique in which crop plants, crop seeds and weed plant populations are georeferenced in the field and stored in a map. This map could facilitate weed control actions and management decisions. Several research studies can be found using these core technologies in the development of mechanical weeding systems (Astrand & Baerveldt, 2002; Griepentrog et al., 2006; Slaughter et al., 2008; Tillett et al., 2008; Van der Weide et al., 2008). Similarly, some automated weeding technologies have been commercialized. For example, the OZ and DINO (Naio technologies), Robovator (F. Poulsen Engineering) and Robocrop (Garford) are some weeding robots available in the market (Melander et al., 2015; Merfield, 2016).

Mechanical weeding is an activity that involves direct physical interaction between the weeding implement and the soil. Though much of the research on mechanical weeding has been focused on improving mechanical weeder systems by enhancing the technology, little work has
been done to understand the effect of interaction between soil and weeder tool on weeding efficacy. Soil-tool interaction has been studied by several investigators using empirical, analytical, and numerical methods. These studies mainly explore the performance of tillage tools, which is measured in terms of draft or input energy (Karmakar & Kushwaha, 2006). Soil-tool interaction studies can help design optimum tillage tools by providing knowledge about draft forces and soil disturbance associated with the design.

For certain active intra-row weeding systems, a weeding tool may need to be actively moved along complex trajectories with accurate control. Control of the tool requires knowledge of draft forces, while ensuring soil disturbance is optimal for higher weeding efficacy. However, the study of control involving soil-machine interaction can be found mostly limited to planter depth control (Anthonis et al., 2004; Hanna et al., 2010). The exploration of the control of ground engaging tools is scarce probably because precise control of these tools is very challenging due to the complex nature of soil-tool interactions, which is further complicated by high variability or uncertainty of the field caused by unstructured environmental and geographical conditions. Consequently, many agricultural practices focus on simple application of these tools without requiring precise control, and therefore extensive investigation on this topic may have been deemed unnecessary.

However, as the demand for fully autonomous agricultural vehicles or agricultural robots will grow in the future, it may become more important to understand soil-tool interactions and their impact on several agricultural activities. Particularly, precise control of tools in the soil could become an integral part of autonomous agricultural operations, and hence understanding interaction between soil and tools will become pivotal for improving performance of agricultural
activities. Therefore, exploring soil-tool interactions and their application in control of tools could be beneficial for many agricultural practices.

Since mechanical weeding involves interaction between soil and weeding tools, its performance depends on soil properties, tool properties and soil-tool interactions. The objective of this research was to use mechanical weeding as a case study of soil-tool interactions to explore different aspects of the interactions and their impact on weeding performance, with a larger goal of extending this knowledge to other areas of agriculture where the research outcomes could be valuable.

**Objectives**

The goal of this research was to investigate two aspects of soil-tool interaction, namely (1) forces and (2) soil disturbance in assessing performance of a rotating tine mechanism intended for automated intra-row mechanical weeding. The specific objectives of this research were to:

1. Study weeding performance of a single tine and rotating tine mechanism using simulated weeds at different tine parameters and operational settings. The performance of a single tine was investigated for different tine diameters, working depths and travel speeds, and that of rotating tine mechanism was investigated at different working depths and rotational speeds.
2. Develop mathematical models to predict force on a tine of a rotating tine mechanism operating at different longitudinal velocity and speed ratios (ratio of peripheral to longitudinal velocity). The models were studied by comparing parameters of the models and determining performance of the models in estimating soil reaction forces at different operational settings.
3. Investigate the effects of longitudinal and rotational velocities on soil draft force, soil resistance torque and power of a rotating tine mechanism consisting of vertical tines in loam soil.

**Dissertation Overview**

This dissertation consists of six chapters. Chapter 1 contains a general introduction to the research. In Chapter 2, the background of the research is presented. This chapter describes different aspects of mechanical weeding and soil-tine interactions. Chapter 3 contains a journal article entitled *Investigating Effects of Interaction of Single and Rotating Tine Mechanism with Soil on Weeding Performance using Simulated Weeds*. Chapter 4 contains a journal article drafted for publication entitled *Modeling Soil Forces on a Rotating Tine Mechanism in Artificial Soil*. Chapter 5 contains another journal article drafted for publication entitled *Investigating Effects of Rotational and Linear Velocities of a Vertical Rotating Tine Mechanism on Soil Reaction Forces for Field Cultivation*. Chapter 6 contains general conclusions and recommendations for future work.
CHAPTER 2. BACKGROUND

Crop plants play a vital role in human livelihood. They can be used as food for human consumption, feed for livestock, and fibers, oils and other products for personal and industrial uses. Therefore, crops are very important for sustenance and economic development. According to the data published by Economic Research Service (ERS) of USDA, the total cash receipts from crops in the United States in 2018 was US$196.2 billion. The two highest cash receipts were from corn and soybean. The cash receipts for corn and soybean were US$48.9 and US$37.2 billion respectively, which accounted for more than 40 percent of the total cash receipts from all crops in the United States. Similarly, specialty crops such as fruits, vegetables, true nuts, horticulture, and nursery crops comprised one-third of crop receipts and one-sixth of receipts for all agricultural products in 2017 in the United States at US$64.7 billion (Astill et al., 2020).

Lack of weed management can be a major problem for crop production and its profitability. Weeds growing close to the crops can compete for nutrients, water and sunlight against crops diminishing their development and yield (Slaughter et al., 2008). The quality of crops can also substantially decrease due to limited amount of resources available for their survival. This decrease in yield and quality can affect the profits that can be generated from these crops. Studies conducted by Soltani et al. (2016) showed that if weed-management tactics are not implemented to control interference of weeds with corn plants, there can be 50% or approximately US$26.7 billion reduction in the corn yield annually in United States and Canada. Similarly, another study performed by Soltani et al. (2017) showed that a lack of weed management tactics for soybean can reduce soybean yield by approximately 52%, which accounts to a US$16 billion reduction in receipts annually in the United States, and approximately 38%, or US$0.4 billion annually in Canada. The specialty crop production
typically produces high-value output from relatively small areas of land. Therefore, if weeds are not managed or poorly managed for specialty crops, a substantial loss can occur in the earnings from growing these crops.

**Weed Control**

Therefore, weed control is a very important agricultural activity performed for high yield and quality of crops. There are several methods of weed control such as manual weeding, chemical, biological, thermal and mechanical. Among these methods, chemical and mechanical weeding are currently the most relied upon techniques in conventional cropping systems (Young et al., 2014).

**Chemical Weed Control**

In chemical weed control, herbicides are applied to control weeds. The application of herbicides for weed control started being adopted after World War II (Gianessi & Reignier, 2007). After World War II in the U.S., people moved to big cities looking for jobs, which led to a scarcity of labor in rural areas and labor costs increased. The application of herbicides was a relatively inexpensive and highly effective method; and therefore, it became a more favorable method for controlling weeds. Furthermore, before the development of herbicides farmers had to know different aspects of weed control, such as what kind of weed management to implement, when to apply different weed control strategies and what kind of observations are needed for making proper weed control decisions. Chemicals that could kill weeds on contact or through movement within the plant served as a convenient way to control weed and thus, farmers required less knowledge for managing weeds (Young et al., 2014). Therefore, the use of herbicides reduced time, effort and cost of managing weeds for the growers. Historically, chemical weed control has been found to be more economical and helpful in reducing yield loss
compared to mechanical cultivation or manual weeding (Gianessi & Reigner, 2007). As a result, it remains one of the most relied upon methods for controlling weeds.

Despite the effectiveness of chemical weed control, alternative methods are being sought because the usage of herbicides has been associated with environment damage, reduced water quality and loss of genetic diversity (McErlich & Boydston, 2014). Excessive use of herbicides has also led to herbicide resistant weeds which is now the major concern for farmers relying on chemical weed control (Young et al., 2014). In some places, the acceptability of herbicides application has been diminished due to consumer concerns and growing interests in organic foods resulting in stricter regulations in pesticide usage (Slaughter et al., 2008).

**Mechanical Weed Control**

In mechanical weeding, machines are used for controlling weeds. There are many types of mechanical weeders available today which are designed to be mounted on the tractor as the source of draft and power. These weeders primarily control weeds using three main physical techniques: (1) burying, (2) cutting and (3) uprooting (Ahmad et al., 2014). Burying impedes growth of weeds by covering them with a layer of soil. Weeds are buried by the action of tillage tools (Gianessi & Sankula, 2003), especially performed during land preparation. Tillage, besides burying weeds, enhances soil conditions by reducing soil strength, covering plant residues and rearranging soil aggregates. Cutting kills weeds by shearing them off, while uprooting dislodges weeds from soil, thus depriving them of nutrients and resources required for further development. Both cutting and uprooting are achieved by mechanical cultivation after planting and emergence of crops. Mechanical weeding can be divided into two types based on where the weeders are applied with respect to the crops. The two types are: (1) inter-row weeding and (2) intra-row weeding (Ahmad et al., 2014).
Inter-row Weeding

Inter-row weeding is a weeding method performed between the crop rows (inter-row). Inter-row weeding is the most common method of mechanical weeding employed by the growers who do not use herbicides or involved in organic farming. Therefore, the majority of weed control implements are designed for inter-row weeding (Cloutier et al., 2007). For inter-row weeding, it is desirable to cultivate as much of the inter-row area as possible to maximize the amount of weed destruction but without any damage to the crop. However, this introduces some limitations to using this method. For example, weed control is only feasible during early crop stages because limited tractor and cultivator ground clearance and machine-crop plant contact may potentially damage the crop foliage at later growth stages. Despite these limitations, there exist a wide selection of cultivation implements or tools for mechanical inter-row weeding. The most common machines used for mechanical weed control are inter-row cultivators, which use cultivating tools mounted on a toolbar that either rotate or sweep to move soil, bury, cut or uproot the weeds (Bin Ahmad, 2012).

Intra-row Weeding

Intra-row weeding is performed to control weeds within or near the crop rows. Intra-row weeding is more difficult to implement compared to inter-row weeding because it requires control of weed plants growing close to the crops in a row. There are few machines available for intra-row weeding (Bin Ahmad, 2012) due to the challenges associated with intra-row weeding. The implements for intra-row weeding can control weeds using two different approaches that depend on the crop density. The first approach involves application of selective machines or add-on tools that do not require lateral actuation for intra-row weed control. In the second approach, machines can be used with weeding tools that move laterally to conduct weed control around the crop canopy.
There are different designs of intra-row weeders that have been found to be effective for weed control. The finger weeder, for example, is an intra-row weeder consisting of two sets of steel cone wheels with rubber spikes pointing horizontally outward at an angle (Fig. 2.1(a)). The rubber fingers penetrate the soil below the surface and works most effectively against young weeds. The weeder performs best in loose soil and poorly in heavily crusted and compacted soils or where heavy residue is present. The torsion weeder is another machine for intra-row weeding which uses a rigid frame with spring tines connected and bent so that two short tine segments are parallel to the soil surface and meet near the crop plant row (Fig. 2.1(b)). The coiled spring tines allow the tips to flex with soil contours and around established crops. For both finger and torsion weeders, to effectively damage weeds close to the crop rows, the tractor or vehicle propelling the weeder must be guided very accurately relative to the crop row (Bowman 1997; Cloutier et al. 2007; Van der Weide et al. 2008). Similarly, the brush weeder is another intra-row weeder that uses flexible brushes made of fiberglass or nylon that rotate about vertical or horizontal axes to damage weeds (Fig. 2.1(c)). The weeder mainly uproots but can also bury and break weeds. An operator is required for accurate steering and control of brushes for weeding (Melander 1997; Cloutier et al. 2007). The ECO-weeder is an intra-row weeder mounted to three-point hitch and trails behind a tractor (Fig. 2.1(d)). The weeding is performed by moving two rotating discs with vertically oriented tines in and out of the crop row. The controlled movement of the disc around crop plant is performed by an operator, while disc rotation is powered by a belt system driven by the tractor’s power take-off PTO (Ahmad et al., 2014).

The automation for intra-row weed control is a topic of interest because of the high cost and reduced availability of labor, environmental concerns and growing demand for organic products (Perez-Ruiz et al., 2012). As a result, there have been increases in research efforts to
develop effective automated or robotic intra-row weeding systems. Research can also be found focusing on integrating different aspects of technology to develop automatic or robotic intra-row weeder (Melander et al., 2015; Astrand & Baerveldt, 2002; Griepentrog et al., 2006). Some automated weeding technologies have been commercialized. For example, the OZ and DINO (Naio technologies, Escalquens, France), Robovator (F. Poulsen Engineering, Hvalsoe, Denmark) and Robocrop (Garford, Peterborough PE6 8RP, UK) are some weeding robots available in the market (Melander et al., 2015; Merfield, 2016).

Figure 2.1. (a) Finger weeder (Van der Weide et al., 2008), (b) torsion weeder (Van der Weide et al., 2008), (c) brush weeder (Melander, 1997) (d) ECO weeder (Ahmad et al., 2014).
Robotic Weeding

With continuous advancement in automation technology, fully automatic or robotic intra-row weeders could be developed in the future that can eliminate human intervention, reduce time consumption, and damage the maximum number of weeds very close to the crop plants. However, Merfield (2016) described limitations with the current approach to robotic weeder development. One of the problems he points out is that less emphasis is given to the weeding component of the machinery to the extent that it appears to be an “afterthought.” The weeding component that makes direct contact with the soil and weed is the most essential part of mechanical weeding. The design and operational settings of the weeding component can considerably affect efficacy of intra-row weeding.

However, there are many designs of weeders for intra-row weed control (Astrand & Baerveldt, 2002; Griepentrog et al., 2006; Cloutier et al., 2007; Tillett et al., 2008; Slaughter et al., 2008). The abundance of the intra-row weeder designs can create confusion among the growers in determining and selecting the proper design for their application. In addition to weeder selection, the growers must also learn different operational settings of the weeder and determine those that will yield the best result (Merfield, 2016). The efficacy of the design depends on its potential to damage the weeds through either direct contact with the weeds or indirectly by disturbing the soil. If weeding is accomplished through soil disturbance, the disturbance should not damage the crop plants. Soil disturbance depends on the interaction between the soil and the tool engaged in the soil. Soil conditions are contingent upon the weather and thus, are highly variable. Therefore, even if the best operational setting is identified for a weeder, the performance may alter or possibly decline under different soil conditions. Efficacy may also be impacted by the species of weeds and crops, and the timing of the weeding relative to crop growth because different magnitudes of soil disturbance may be required for variation of
these cases to meet the objectives of high weed control efficacy and low crops damage for intra-row weeding.

One approach to improving intra-row weeder design is to study the interaction between soil and weeder tools. By understanding this interaction under different soil conditions and tool settings, it may be possible to achieve desired soil disturbance required for better weeding performance. The soil reaction forces acting on the weeding tool is another aspect of intra-row weeding that determines how precisely the weeder can be moved close to the crops. Since the soil force depends on soil properties, tool parameters and operational settings, studying soil-tool interaction can help discover dynamics associated with the weeder tool and make better decisions for optimal performance.

**Soil-Tool Interaction**

Soil disturbance and forces developed at the interface of the soil and the tool are two important aspects of soil–tool interaction (Ani et al., 2018). In mechanical weeding, mechanical forces delivered to the soil are required to accurately maneuver the weeding tool and create soil disturbances that are sufficient to harm the weeds but not the crops. Therefore, forces and soil disturbance play an important role in mechanical weeding. Literature can be found exploring these two aspects for tillage operations (Godwin et al., 1984; Manuwa & Ademosun, 2007; Dedousis & Bartzanas, 2010). Soil resistive forces and soil disturbance can be impacted by soil properties and conditions, tool geometry and tool operating conditions. Since tines were part of the weeder investigated in the research, the discussion that follows will be focused on that interaction of tines with the soil.

A tine is a tillage tool with a soil loosening effect that reaches considerably further than the width of the tine body (Fig. 2.2(a); Koolen & Kuipers, 1983). Tines are used in chisel plows, subsoil plows, liquid injection, seeders, spike tooth harrows, and planters (Al-Neama, 2019).
Godwin and O'Dogherty (2007) classified tines into three categories according to the depth/width (d/w) ratio as follows:

1. Wide tines (blades) for which d/w < 0.5
2. Narrow tines (chisel) for which 1 < d/w < 6
3. Very narrow tines (knife) for which d/w > 6

Different types of soil failure patterns have been identified and described in the study of soil and tool interaction (Elijah & Weber, 1971; Koolen & Kuipers, 1983; Aluko & Seig, 2000; Stafford, 1984; Karmakar & Kushwaha, 2006). The soil can fail in different patterns in front of a tine depending on soil state and tine operating conditions. The operating conditions that can affect soil failure (Fig. 2.2(b)) are rake angle (α), working tine depth (d) and tine travel speed.

Shear failure (Fig. 2.2(b)) is the failure pattern emphasized by several researchers to develop soil cutting forces that were modeled using soil and tool parameters (Payne, 1956; Hettiaratchi & Reece, 1967; Godwin & Spoor, 1977; McKyes & Ali, 1977). In shear failure, the soil is under compressive stresses, due to a moving tine at certain rake angle α, and fail when the applied load becomes sufficient to overcome the shear strength of the soil. A failed soil block, with certain forward rupture distance (r) in front of a tine and sheared plane angle (β) with the horizontal soil surface, separates and moves ahead of the tine. The process is repeated with continuous movement of the tine until another block of soil is sheared off. The vertical pressure or load exerted by the failed soil block is the surcharge (q) of the soil.
Soil Reaction Forces

Several methods have been used to evaluate forces on a tine operating in the soil. Karmakar and Kushwaha (2006) categorized force prediction models into three methods based on the approach used to study these forces, which are as follows:

1. Analytical method
2. Numerical method
3. Empirical method

1) Analytical Method

The limit equilibrium method is one of the most important analytical approaches of studying soil-tool interaction (Shen & Kushwaha, 1998). In this method, driving and resisting forces during soil failure are quantified and analyzed along a failure surface at a static equilibrium condition. In most analytical methods, the soil failing in front of the tool is broken into several parts considered as rigid objects. The force equilibrium equations are established over the entire system with soil in the failure zone assumed to be in the limit state where its

Figure 2.2. (a) Cross section of typical tine failure soil profile (adapted from Godwin, 2007). The width of soil disturbance for the tine exceeds the tine body. (b) Shear soil failure (initial failure) with single soil block in front of a tine (adapted from Stafford, 1984), where d is working soil depth, w is tine width, r is rupture distance, q is surcharge, α is rake angle and β is soil shear plane angle.
resistance becomes largest. The equilibrium equations are then solved to calculate forces acting on the tool.

For application of the limit equilibrium method, soil failure is assumed to take place inside the soil body and at a metal-soil interface. The equations of forces at the soil failure surface and the metal-soil interface form the basis for determining forces due to soil-tool interaction. The force at soil failure surface is based on Coulomb’s law of soil shear strength. Coulomb assumed that the soil shear strength was composed of two components: cohesion and friction (Mckyes, 1985). Cohesion is the component of the shear strength independent of any external pressure due to forces of attraction between soil particles. Friction is the shear strength component that is proportional to the applied pressure due to resistance that develops when soil particles slide over one another. Mohr extensively studied theory of material strength and developed a generalized theory that captured Coulomb’s idea relating stresses on soil failure planes to cohesion and friction (Yu, 2002). Therefore, in many articles on soil-tool interactions, this theory is known as Mohr-Coulomb criterion. According to the Mohr-Coulomb criterion, the forces on a failure surface in the soil body are determined by:

\[ \tau = c + \sigma_n \tan \phi \]  

where, \( \tau \) = soil shear stress at failure,
\( c \) = cohesion,
\( \sigma_n \) = normal stress on the failure plane, and
\( \phi \) = internal frictional angle of soil.

The forces interacting on the interface of metal and soil are determined by:

\[ \tau = a + \sigma_n \tan \delta \]  

where, $a = \text{adhesion at a soil-tool interface}$,

$\sigma_n = \text{normal stress on the failure plane}$, and

$\delta = \text{external frictional angle at a soil-tool interface}$.

Several studies have been conducted applying the limit equilibrium to study soil-tool interaction using two-dimensional and three-dimensional soil failure models.

**Two Dimensional Models**

The first soil cutting model was developed for two-dimensional soil cutting based on Terzaghi's passive earth pressure theory that was developed for the evaluation of soil loads in civil engineering (Terzaghi, 1943). The model assumed soil movement in the forward and upward directions only. For the model, the soil in front of the tool and failure surface was assumed to consist of two parts: (1) the Rankine passive zone and (2) the shear zone bounded by logarithmic spiral curve (Fig. 2.3). The resulting forces of the tool can be calculated by solving the equilibrium equation of forces acting along the boundaries of the two parts and on the soil body.

---

**Figure 2.3.** Logarithmic spiral failure zone (adapted from Shen and Kushwaha, 1998).
Reece (1965) developed a universal earth-moving equation based on the two-dimensional method as follows:

$$P = (\gamma d^2 N_\gamma + c d N_c + c_a d N_{ca} + q d N_q) w$$

(3)

where $P$ is the soil cutting force,

$\gamma$ is the total specific weight of the soil,

$d$ is the working soil depth,

$c$ is soil cohesion,

$c_a$ is soil-metal adhesion,

$w$ is the width of tool, and

$q$ is the surcharge pressure vertically acting on the soil surface.

The parameters $N_\gamma, N_c, N_{ca}$, and $N_q$, are dimensionless factors denoting gravitational, cohesive, adhesive, and surcharge components of the soil reaction, respectively and are functions of geometry of the soil-tool interfaces, soil internal frictional angle and soil-metal frictional angle (Hettiaratchi et al., 1966). Hettiaratchi et al. (1966) provided a set of charts with calculated values of N-factors. A modified version of the soil cutting force in equation (3) was presented by Hettiaratchi and Reece (1974) by combining the adhesive and cohesive terms because the magnitude of soil-metal adhesion was very small (Al-Neama, 2019).

The two-dimensional method of soil failure analysis is valid for wide soil cutting tines with depth/width ratio of less than 0.5. For narrow and very narrow tines the soil failure in front of a tine moves not only horizontally and vertically, but also sideways in the direction of tine width. Therefore, to evaluate forces on narrow and very narrow tines, several semi-empirical models were developed using three-dimensional soil failure.
Three Dimensional Models

Three-dimensional soil failure postulated for different models consisted of several blocks or zones of soil. The shape and formation of these blocks were found to vary at different working depths of a tine. For a tine operating in the soil, there was a depth above which the soil failure was observed to move forward, upward, and sideways, while below this depth the soil moved laterally (Fig. 2.4) (Godwin & Spoor, 1977). The tine depth where the transition of soil failure occurred was referred to as the critical depth. Godwin and Spoor (1977) found critical depth empirically, however its location is not known in general (Godwin & O'Dogherty, 2007).

The first three-dimensional soil failure model was developed by Payne (1956). A model with critical depth was proposed by O'Callaghan and Farrelly (1964). Hettiaratchi and Reece (1967) proposed a three-dimensional soil failure model consisting of forward failure and transverse failure. The resultant of forces from the two failures were used to calculate total force on a tine. The force contribution of forward failure was same as the universal earth moving equation (Equation 3).

The Godwin-Spoor model considered two separate failure patterns with narrow tines: (1) three-dimensional crescent failure above the critical depth and (2) two-dimensional lateral failure below the critical depth (Fig. 2.4; Godwin & Spoor, 1977). A modified form of equation (3) was developed to calculate forces on a narrow tine for three-dimensional crescent failure. An equation was also proposed to calculate forces for two-dimensional lateral failure. To apply the Godwin-Spoor model, prior knowledge of the rupture distance, r, is required, which is generally considered difficult to obtain (Shen & Kushwaha, 1998).
Mckyes and Ali (1977) proposed a model similar to Godwin and Spoor with soil failure consisting of a center wedge and two side crescents. The equation to calculate force was identical to equation (3) except without adhesion components. Moreover, the values of N-factors were re-evaluated by developing new equations to compute the factors, which are given as follows:

\[
N_r = \frac{r}{2d} \left[ 1 + \frac{2r}{3w} \sin \eta \right] \frac{\cot(\alpha + \delta) + \cot(\beta + \phi)}{\cot(\alpha + \delta) + \cot(\beta + \phi)}
\]  

\[
N_c = \frac{[1 + \cot \beta \cot(\beta + \phi)] [1 + \frac{r}{w} \sin \eta]}{\cot(\alpha + \delta) + \cot(\beta + \phi)}
\]  

\[
N_q = \frac{\frac{r}{w} \left[ 1 + \frac{r}{w} \sin \eta \right]}{\cot(\alpha + \delta) + \cot(\beta + \phi)}
\]

where, \(d\) is operating depth,
\( \eta \) is angle of the crescent element from the direction of travel, and

\( r \) is the rupture distance, which is given by:

\[
  r = d ( \cot \beta + \cot \alpha )
\]  

(7)

Compared to the model by Godwin and Spool, prior knowledge of rupture distance was not required for this model because it could be computed numerically (equation 7).

Another model was proposed by Perumpral et al. (1983) for a narrow tine in which the failure zone only included a center wedge. The researchers claimed the model was similar to Mckyes and Ali (1977) and Godwin and Spoor (1977); however, the side crescents were replaced by two sets of forces acting on the sides of the center wedge (Grisso & Perumpral, 1985). The force equation for the model was similar to equation (3) excluding surcharge components. For the model, new equations were developed for \( N \)-factors, which are given as follows:

\[
  N_y = \frac{A}{wd^2} \left[ 2(1 - \sin \phi) z_a \sin \phi + w \sin(\beta + \phi) \right] \frac{\sin(\beta + \alpha + \delta + \phi)}{\sin(\beta + \alpha + \delta + \phi)}
\]  

(8)

\[
  N_c = \frac{\cos \phi \left[ \frac{2A}{wd} + \frac{1}{\sin \beta} \right]}{\sin(\beta + \alpha + \delta + \phi)}
\]  

(9)

\[
  N_a = \frac{-\cos(\beta + \alpha + \phi) \left[ 1 + \frac{h}{d} \right]}{\sin(\beta + \alpha + \delta + \phi)}
\]  

(10)

where, \( h \) is height of soil heave in front of the tool at failure,

\( A \) is area if each side surface of the central wedge, and
\( z_a \) is average depth at which the centroid of the failure wedge is located from soil surface:

\[
z_a = \frac{1}{3}(z + h)
\]  

(11)

The models discussed above were developed for quasi-static condition corresponding to slow tine speed in which the effect of travel speed was not considered. Stafford (1979, 1984) proposed dynamic models for both two and three-dimensional soil failure cases based on Hettiarratchi and Reece’s static models by including the force required to accelerate the soil particles in front of the tool. Swick and Perumpral (1988) proposed a dynamic soil cutting model which included the speed effects. The failure zones for the model consisted of a center wedge and two side wedges. Zeng-Yao (1992) developed another dynamic model which included the effects on the reaction forces due to acceleration and shear strain rate. Wheeler and Godwin (1996) developed models for single and multi-narrow tines operating at speeds until 20 km/h based on the model developed by Godwin et al. (1984). In their paper, Wheeler and Godwin presented modified version of equation (3) with addition of inertial force component, which accounted for the force on a tine due to significant travel speed. The equation is given as follows:

\[
P = (\gamma d^2 N_y + c d N_{ca} + q d N_q + \gamma v^2 d N_a) w
\]  

(12)

where, \( v \) is tine velocity,

- \( N_{ca} \) is dimensionless factor for cohesive and adhesive soil reaction component, and
- \( N_a \) is dimensionless factor for inertial soil reaction component.

Although the analytical models developed discussed above can be useful for approximating forces for many cases, they have some intrinsic weakness (Shen & Kushwaha, 1998). The models are based on assumptions of soil failure geometric patterns which vary for
different investigators. The models do not describe the effect of tool speed on modes of soil failure which can vary the failure profiles. Further, the limit equilibrium approach used for developing the models can only provide information on maximum forces generated inside the soil body without providing any knowledge on deformation of the soil body. The analytical models were based on simplified flat blade, neglecting standard tine shapes such as curved or winged tines (Al-Neama, 2019). Therefore, the models may be limited to evaluating forces on simple tine geometries (Karmakar & Kushwaha, 2006).

2) Numerical Methods

Currently, numerical methods are gaining more credibility in the investigations of soil-tool interaction because of the progress in computer technology which have made them possible. Also, with the help of suitable mathematical models and numerical methods, many practical problems associated with the interaction have been solved. Constitutive models are typically developed in numerical methods of soil failure modeling to describe the relationship between applied stresses and resultant strains within the soil. Unlike analytical methods, simplification may not be required for the development of models using numerical methods. Therefore, numerical methods can be used to address challenging aspects of soil-tool interaction studies such as complex tool geometry, soil behavior and processes involved in the interaction.

Karmakar and Kushwaha (2006) reported four numerical methods that are used to solve soil-tool interaction problems. These are the finite element method (FEM), the discrete element method, computational fluid dynamics (CFD) and artificial neural networks (ANN). In FEM, continuum mechanics is applied (Ani et al., 2018). FEM has been used by several researchers to study soil-tool interaction for complex tool shapes and soil behaviors (Shen & Kushwaha, 1998; Upadhyaya et al., 2002; Abo-Elnor et al., 2004; Bentaher et al., 2013). The soil particles in FEM are assumed to connect and act like one object; however, during actual field operation several
large fragments of soil may form and displace independently. In such cases, FEM may not be able to handle numerical convergence (Chen et al., 2013; Abo-Elnor et al., 2004).

The DEM has been used to simulate soil–tool interactions in many applications such as bulldozing and agricultural operations (Ani et al., 2018). In DEM, soil is modeled as collections of discrete particles with each particle interacting with the neighboring particles under external forces (Mak et al., 2012). As a result, forces develop at the point of contact between particles leading to their displacement. The motion of each particle follows Newton’s second law (Chen et al., 2013). The contact force magnitude depends on particle properties and overlap between them. Unlike the FEM, the DEM allows displacement of large particles and crack propagation involved in soil-tool interaction (Abo-Elnor et al., 2004). In general, the DEM is considered by many researchers as a promising method for studying soil-tool interaction (Ani et al., 2018).

CFD was applied by Karamakar and Kushwaha (2005) to show the potential of the method in studying soil-tool interaction. In their research, soil was characterized as a visco-plastic material, and the soil flow pattern was determined around the tool. For CFD analyses, fluid flow was considered to mimic non-Newtonian fluid flow behavior. ANN is another numerical method that has been investigated by researchers to study different aspects of soil-tool interaction (Zhang & Kushwaha, 1999; Farfani et al., 2015). In ANN, a model is developed, in which relation between input and output are computationally derived from large sets of experimental data with the help of some mathematical functions. Zhang and Kushwaha (1999) used ANN to study tillage draft at high operating speed using the radial basis mathematical function.

3) Empirical Method

In this method, all the physical parameters that affect the process of interest for soil-tool interactions are identified, and their relation is explored using experimental data. The relation
between them is expressed by a curve that best fits the observed data and appropriate regression model is developed (Karmakar & Kushwaha, 2006). In this context, similitude or dimensional analysis is used and is a technique in empirical methods in which all pertinent physical quantities impacting the process are identified and later consolidated into dimensionless groups (Al-Neama, 2018). The relationship between the variables representing each dimensionless group and the process is investigated.

Dimensional analysis has been used by several researchers to reduce the number of independent variables involved in the study (Osman, 1964; Hettiaratchi et al., 1966; Sprinkle et al., 1970; Upadhyaya et al., 1984; Moeenifar et al., 2013). Force prediction models have been developed for static (Osman, 1964; Hettiaratchi et al., 1966) and dynamic cases (Sprinkle et al., 1970; Upadhyaya et al., 1984).

Upadhyaya et al. (1984) studied draft force on a passive chiseling tine and found the force to be function of operation conditions, tool geometry, and soil properties. In the study, cone index was used as one of the parameters. They assume that soil properties, such as shear stress, bulk modulus, texture, internal friction angle, and soil metal friction angle, and soil physical condition, such as bulk density and moisture content, are related to the cone index. Although empirical method using dimensional analysis could be used to develop a solution for a specific condition, it may not provide any general solution (Al-Neama, 2019).

The magnitude of forces on the tines are affected by tine geometry such as width and shape and by tine operating conditions such as working depth, speed and rake angle. In general, the draft force increases with tine width. Koolean and Kuipers (1983) showed that draft force increases linearly with tine width. Godwin (2007) demonstrated a curvilinear relationship between tine width and draft force based on depth/width ratio relationships. He showed forces
increased in proportion to tine width for very narrow tine width range, then at a decreasing linear rate for narrow tine and wide tine width ranges. Desir (1981) reported strong interaction effects between tine width and depth on draft force. Therefore, several studies can be found focusing on the effect of width and depth combinations on draft force rather than individually (Payne, 1956; McKyes & Ali, 1977; Godwin & Spoor, 1977; McKyes & Desir, 1984). The shape of a tine can influence stress distributions in soil, and also determines the flow of soil particles with respect to the tine. The magnitude of draft forces for different shapes of tines can be primarily described by the soil to metal friction owing to the shapes (Sharifat, 1999).

Increases in working tine depth increases the draft force. The force can increase linearly or quadratically depending on type of the soil in which the tine is engaged (Al-Neama, 2018). Koolen and Kuipers (1983) showed the draft force increased linearly in non-cohesive soil and quadratically in cohesive soil. Godwin and Spoor (1977) showed how the force on a tine increases, by including a force component for lateral failure, when the tine operates below its critical working depth. Working below critical depth is considered undesirable from agronomic point of view (Dedousis & Bartzanas, 2010). Further, Godwin (2007) recommends never working the equipment deeper than necessary.

The draft force increases with tine speed, which is often attributed to the acceleration of soil particles (Dedousis & Bartzanas, 2010). Several researchers have found linear, quadratic, parabolic, or exponential relationships between the draft force and the speed, the differences of which have been attributed to variation in soil properties and operation conditions (Al-Neama, 2019). The contribution of inertial force due to velocity on the total draft force may not be significant under slow speeds. Schuring and Emori (1964) reported the inertial force on a tine was negligible for speeds below $\sqrt{5gw}$, where $w$ is width of the tine and $g$ is acceleration due to
gravity. Wheeler and Godwin (1996) recommended to increase critical speed to 
\[ \sqrt{5g(w + 0.6d)} \], where d is the working depth.

Godwin (2007) showed both horizontal and vertical forces increase with rake angle.

Several studies have focused on the effects of rake angle on draft requirements (Payne & Tanner 1959; Godwin & Spoor, 1977; Stafford 1979; Stafford 1984; Onwualu & Watts, 1998; Aluko & Seig, 2000). Godwin (2007) suggested designing the implement with low rake angle for low draft and good soil penetration.

**Soil Disturbance**

Information on soil disturbance and the factors affecting it are important for mechanical weeding. A tool engaged in the soil can cut the soil, develop heaps of loose soil around its point of contact and throw soil. All these activities can affect weeds and crops. Soil disturbance has been widely investigated by several researchers (Godwin & Spoor, 1977; Mckyes, 1985; Solhjou et al., 2013; Manuwa, 2009; Al-Neama, 2018). Numerous research papers focus on the soil profile after tillage because it provides knowledge about soil movement and the desired soil disturbance (Al-Neama, 2019). Solhjou (2013) reported tool geometry (width and rake angle), tool settings (speed and working depth) and soil condition (texture, moisture, and structure) as important factors affecting the soil profiles.

Differences in tool geometry can result in different soil profiles and soil disturbances (Al-Neama, 2018). Increasing tine width increased the width and area of the furrow for curved and plane tines (Willatt & Willis, 1965). For soil failing in the form of a shear plane, the soil disturbed around a tine can be evaluated using the analytical method developed by several researchers (McKyes & Ali, 1977; Godwin & Spoor, 1977; Swick & Perumpral, 1988). The width of the soil cut by the tines for these cases could be approximated as the distance between
two extremes of the side crescents proposed by the investigators. Godwin (2007) showed that the depth/width ratio can affect the patterns of soil failure. Based on soil failure patterns presented by Godwin (2007), the width of soil failure or furrow increases with depth for narrow tine, however, for a very narrow tine the width do not change when the working depth is below the critical depth for the tine.

Similarly, rake angle affects the pattern of soil disturbance. Godwin (2007) showed the width of soil disturbance was higher for rake angles of 90° and 20° than 160° for tines of smaller depth/width ratio. He also showed the volume of soil disturbed in front of the tine increased with decreases in rake angle. Increasing tine speed can increase soil disturbance and soil throw (Al-Neama, 2019). Swick and Perumpral (1988) developed an expression to calculate the maximum width of side wedges (crescents) based on rupture distance and tool angle for their proposed dynamic soil failure model. Thus, this expression could be used to evaluate width of soil failure for tines operating at certain speeds.

Besides the tool geometry and operating conditions, soil properties such as soil moisture content, soil compaction, soil type, soil cohesion, soil adhesion can also influence soil profiles. The soil could fail in different patterns depending on soil parameters (Elijah & Weber, 1971), which could alter the soil profiles. Soil moisture content was found to have inverse relationship with maximum width of soil throw, while increasing soil compaction resulted in increase in maximum width of soil throw (Manuwa & Ademosun, 2007).
CHAPTER 3. INVESTIGATING EFFECTS OF INTERACTION OF SINGLE TINE AND ROTATING TINE MECHANISM WITH SOIL ON WEEDING PERFORMANCE USING SIMULATED WEEDS

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Abstract

Mechanical weeding augmented with automation technology should result in highly effective weeding systems. However, the interaction between controlled weeding mechanisms and soil and weeding performance is not well understood. Moreover, soil is highly variable and makes studying this interaction challenging. The main objective of this research was to develop a method to investigate the effects of mechanical tool-soil interaction on weeding performance for different operating conditions in a controlled environment. Experiments were conducted in an indoor soil bin with loam soil, and weeding performance was studied using small wooden cylinders as simulated weed plants. The investigations featured a single cylindrical tine and a rotating tine mechanism, vertically-oriented and inserted into the soil. Total width of soil disturbance and potential weeding rate were evaluated for the single cylindrical tine at different levels of operational factors namely: tine diameter (6.35 mm, 7.94 mm and 9.53 mm), working soil depth (25.4 mm, 50.8 mm and 76.2 mm) and tine speed (0.23 m/s and 0.45 m/s). Potential weeding rate was examined for the rotating tine mechanism across two operational factors: working soil depth (25.4 mm and 76.2 mm) and rotational speed (25, 50 and 100 rpm). Statistical analysis was performed using ANOVA at p < 0.05. A simulation of the rotating tine mechanism was developed which estimated disturbed area. For the single tine, soil disturbance width was independent of the test speeds; however, diameter and depth had significant effects as the width increased with increased levels of these two parameters. All three parameters had significant
effects on potential weeding rate of the single tine, and the rates were observed to increase for higher levels of the operating parameters. For the rotating tine mechanism, both depth and rotational speed were significant. The potential weeding rate for the mechanism was found to increase for higher levels of these parameters. Although the width of soil disturbance due to a cylindrical tine is affected by tine diameter and working soil depth, operating parameters such as increased longitudinal and rotational speeds also affect plant disturbance. The percentage of disturbed soil area in simulations followed similar patterns as the percentage disturbed plants observed in the experiments.

**Introduction**

Weed control is important for higher crop production. Weeds compete with crops or vegetable plants for nutrients, water and sunlight (Slaughter et al., 2008; Van der Weide et al., 2008) and have a faster growth rate compared to crops (Ahmad et al., 2014). Therefore, proper management is necessary to prevent weed infestation and thus improve crop yield and quality.

Chemical, biological, thermal and mechanical, including manual hand weeding, weed control methods can be used for weed management in agricultural fields. Among these methods, chemical and mechanical weeding are currently the most relied upon techniques in conventional cropping systems (Young et al., 2014). Chemical weed control, which involves the use of herbicides to kill weeds, is an economically effective way to control weeds. However, growing concern about the impact of herbicides on the environment and increasing consumers demand for organic foods has resulted in increased interest in mechanical weed control techniques (Griepentrog et al., 2006; Slaughter et al., 2008; Young et al., 2014).

Mechanical weed control is divided into two weeding strategies based on the spatial relationship between crop and weed plants: (1) inter-row weeding and (2) intra-row weeding (Ahmad et al., 2014). Inter-row weeding is performed between the crop rows, while intra-row
weeding is conducted near and between the crop plants within a crop row. Intra-row weeding is more challenging compared to inter-row weeding because it involves control of weeds growing close to the crop plants without causing excessive crop damage. As a result, increased research efforts can be found focusing on the development of efficacious intra-row weeding systems (Perez-Ruiz et al., 2012). These efforts have also led to the development of automatic intra-row weeding systems with intelligent technologies integrated to minimize human interventions and increase work rates (Melander et al., 2015; Astrand & Baerveldt, 2002; Griepentrog et al., 2006).

Slaughter et al. (2008) organized robotic or automated weeding research into four core technologies: (a) guidance, (b) detection and identification, (c) precision-in-row weed control, and (d) mapping. Vehicle guidance enables accurate positioning of the autonomous vehicle or weeding system required for weeding. Plant detection and identification is required to separate weeds from crop plants. After separating crops and weeds, in-row weeding mechanisms (for mechanical weeding) or spray nozzles (for chemical weed control) are used to precisely target the weed plants and damage their structure disrupting their growth or killing them. Mapping is a technique in which crops, crop seeds and weed population are georeferenced in the field and stored in a map. This map could facilitate weed control actions and management decisions. Several research studies have used these core technologies in the development of mechanical weeding systems (Astrand & Baerveldt, 2002; Griepentrog et al., 2006; Slaughter et al., 2008; Tillett et al., 2008, Van der Weide et al., 2008). Similarly, some automated weeding technologies have been commercialized. For example, the Greenbot (Conver BV), the OZ and COSI (Naio technologies), Robovator (F. Poulsen Engineering) and Robocrop (Garford) are some of the weeding robots available in the market (Melander et al., 2015; Merfield, 2016).
Despite the focus on these technologies and developments to improve mechanical weeding, little work has been done to explore the interaction between weeding implements or tools and the soil with respect to weeding performance of an automated mechanical weeder. Understanding how weeding tools interact with soil can provide key insight into their performance in eliminating or disturbing weed plants. However, there are several factors that make weeding tool and soil interaction studies very challenging, which may also explain why little research has been conducted on weeder tool-soil interaction for autonomous weeding systems. One factor that complicates such studies is the properties of soils, which are dynamic, spatially varying, and thus uncertain. Consequently, investigating soil-weeding tool interaction on uncertain and highly variable soil can result in inconsistent outcomes.

Therefore, controlled experiments could be conducted to examine interaction between weeding tools and soil on weed control performance. Controlled experiments would not only establish better understanding of relationships between interaction and weeding performance for given soil properties, but also aid in the design and development of mechanical weeders for precision weeding. Individual mechanical weeders have specific designs and several adjustable parameters such as tool width, angle, and soil depth. Determining the efficacy of these designs or identifying optimal parameter values for effective weeding may be possible only if the tests are conducted in a controlled environment with consistent soil conditions. Further, the ability to control the experimental conditions may make the experiment less time consuming and inexpensive to establish the efficacy of the weeding system. Therefore, the methodology described in the paper is intended to be the first step in an engineering approach to understand the interactions between tool, soil, and plants and relationships between operational parameters and weeding performance.
The objective of this research was to develop a methodology that could capture interactions between soil and a weeding tool in a controlled environment and evaluate its performance in weeding. The specific objectives were to:

1. investigate the effect of a single tine on width of soil disturbance and potential proportion of weeds damaged with changes in three operational factors: tine diameter, working soil depth and tine speed, and

2. examine the effect of working soil depth and rotational speed on potential proportion of weeds damaged due to a rotational weeding mechanism.

**Materials and Methods**

**Description of soil and soil bin**

Two experiments were performed in a 2.44 m diameter circular soil bin located in the Advanced Machinery Systems Laboratory (AMSL) lab at Iowa State University, Ames, Iowa (Fig. 3.1). A hydraulic power unit was used to rotate the soil bin at different angular speeds. The soil was classified as loam soil with 32% sand, 43 % silt and 24% clay. The soil was sieved to a maximum size of 5 mm. A soil conditioning routine was used, which involved spraying the soil with water and leaving it overnight, to maintain a consistent soil moisture content before the tests. The soil was then mixed using a tiller to a depth of 150 mm and leveled with horizontal scraper blade. This soil preparation process was followed before each test to achieve similar soil conditions for all the tests. The bulk density of soil was 1.27 g/cm³, and the average moisture content was measured to be 17% using the ASTM D4318 standard procedure with an industrial oven.
Experiment with Single tine

The first experiment was conducted to investigate how a single tine disturbs soil while moving linearly and how three operational parameters or factors affect soil disturbance and weeding performance. The factors were: (i) tine diameter, (ii) working soil depth and (iii) tine speed. Cylindrical tines with diameters of 6.35 mm, 7.94 mm and 9.53 mm were used for the test. The three working soil depths were 25.4 mm, 50.8 mm and 76.2 mm. The tine speeds used for investigation were 0.23 m/s (0.5 mph) and 0.45 m/s (1 mph). These speeds were achieved by keeping the tine stationary while rotating the soil bin to achieve the desired test tine speeds. Therefore, the tine speeds were relative to the rotating soil bin. The design of the experiment was completely randomized. The experiment consisted of 18 (3 x 3 x 2) treatments arising from combinations of different levels of the three factors. Each treatment was replicated three times and thus, 54 tests were conducted in total corresponding to 54 (18 x 3) experimental trials.

Figure 3.1. The circular soil bin used for the experiments in which the soil bin was turned and tools remained stationary.
Experiment with rotational weeding mechanism

In the second experiment, a circular rotating tine mechanism was used, and its weeding performance was examined across two operating factors: (i) working soil depth and (iii) rotational speed (rpm) of the mechanism. The mechanism was a steel disc holding four cylindrical tines (Fig. 3.2 (a)). The rotating tine mechanism was designed and developed to function as part of an automatic intra-row mechanical weeder that was developed at Iowa State University (Fig. 3.2(b); Gai et al., 2019). The mechanism affects the intra-row weeds by disturbing the soil through rotation of four vertical tines that are in direct contact with the soil about a vertical axis. The disc of the mechanism was 152.4 mm in diameter and had four 7.94 mm diameter tines which were coaxially arranged and equally spaced around a 127 mm diameter circle. The working soil depth levels used in this test were 25.4 mm and 76.2 mm, and the three rotational speeds of the mechanism were 25, 50 and 100 rev/min. In this experiment, the soil bin was rotated at a specific uniform speed such that the soil moved past center of the mechanism at constant linear speed of 0.45 m/s. This experiment had a completely randomized design consisting of 6 (2 x 3) treatments. There were three replications for each treatment, resulting in a total of 18 experimental trials.

Methodology and set up to measure soil-tine interaction

When a tine is moved in a soil, the soil shears in a specific pattern around the tine. This shearing process is called soil failure (Mckyes, 1985; Hettiaratchi et al., 1966; Godwin & Spoor, 1977). The nature of soil failure depends on soil properties and geometry of the tine (Godwin & O’Dogherty, 2007). The cylindrical tines used in this study were categorized as narrow tines and typical soil failure pattern for such tines can be seen in figure 3.3. The profiles and extent of soil failure or disturbance could vary widely for the operational factors used in this study. However,
it may not be clear how these soil disturbances relate to the weeding performance as the degree of impact on the weed may vary around the tine in different soil disturbance regions.

Figure 3.2. (a) Rotational weeding mechanism consisting of a circular disc with four cylindrical tines. (b) The prototype of automatic intra-row mechanical weeder developed at Iowa State University.

Figure 3.3. Cross section of typical tine failure soil profile (adopted from Godwin, 2007).

To study the impact of operating factors on soil disruption and their subsequent effect on weed plants, thin wooden cylinders were used as simulated small young weed plants. In other research, Paarlberg et al. (1998) used wooden dowels to measure soil movement into crop rows,
and Zhang and Chen (2017) used wooden skewers to measure burial depth of weeds. The experiments associated with both of these studies used inter-row sweeps to affect intra-row weed mortality with burial. In our study, simulated weed plants were used to understand how local soil disturbance affected plant disturbance. This simulated weed approach was advantageous over approaches using real weed plants because it enable the tests to be performed in a controlled manner in less time under similar soil conditions and provide flexibility and control in arranging cylinders in the soil.

The wooden cylinders used in the research did not capture all the biological variations associated with different weed species; however, the focus of this work was on very early weed growth stages when their root structure is relatively weak and can be easily disturbed or damaged through weeding action. This assumption also facilitates estimating damage of weeds due to a single tine because a single tine is more likely to damage young weak weeds by primarily uprooting and sometimes cutting them. To account for different biological variations in the weeds, higher fidelity physical models can be designed and used for simulation or specific plants can be used as surrogate weeds (Brown & Gallendt, 2018).

The wooden cylinders were used for both single tine and rotating mechanism experiments. Each cylinder measured 70 mm in length and 2 mm in diameter. The arrangements of these cylinders were similar in both the experiments. Each experimental trial consisted of five rows of wooden cylinders that rotated along with the soil bin (Fig. 3.4(a)). The cylinders were placed perpendicular to the tine travel path and spaced in the row so that the center cylinder of the row was in line with center of the rotating tine mechanism and the line of action of the tine in the respective experiments (Fig. 3.4(b)). The cylinders were inserted 50.8 mm into the soil in all
the experiments. For the single tine experiment, each row had 15 wooden cylinders inserted into the soil at a uniform spacing of 6.35 mm (Fig. 3.4(b)). However, for the rotating tine mechanism experiment, each row consisted of 21 wooden cylinders uniformly spaced at 12.7 mm apart. More cylinders were used for the rotating tine experiment to capture wider soil disturbance due to larger diameter of the tine mechanism.

![Diagram](image_url)

**Figure 3.4.** (a) Top view of rotational circular soil bin with five rows of wooden cylinders that move along the path of travel and intersect with rotating tine mechanism. (b) The wooden cylinders’ arrangement in a row for single tine experiment.

The effect of the tines on the wooden cylinders was observed, and this effect on each cylinder was classified into five levels according to the cylinder’s orientation and displacement from the original location. Cylinders completely dislodged from the soil were classified as level 5. Those displaced from their original location and tilted were classified as level 4. Level 3 included cylinders that were displaced from their original location but were still oriented vertically. The unmoved but tilted cylinders were classified as level 2. Finally, the cylinders unaffected by the tine mechanism were classified as level 1.
Simulating soil disturbance of rotating tine mechanism

A simulation was performed using a model of the kinematics of the tine mechanism rotatory and linear motion. A model of the motion of each of the four tines in the mechanism was developed to calculate the tine paths for the different rotational speeds and implemented in Matlab script (The MathWorks, Natick, MA). In addition, the effective weeding width from the single tine experiment was used to estimate the soil disturbance area around each tine path. The simulation results were placed into a binary image with black pixels representing areas where the soil had been disturbed and white pixels representing areas where no disturbance occurred (Fig. 3.5) and spatial analysis was used to find disturbed soil area.

The percentage of soil disturbance area over the maximum possible effective area of soil disturbance for all the treatments was compared with the percentage of count of highly impacted simulated weeds from the experiment over the count of simulated weeds (12) that were within the maximum possible effective width. The maximum possible effective area of soil disturbance was the product of the length in the longitudinal direction corresponding to length of a window (Fig. 3.5) selected for spatial analysis and the maximum possible effective width, which was the extent of soil disturbance lateral to tine mechanism linear motion.

![Figure 3.5. Simulation resulted in top view of paths of four tines of a rotating tine mechanism moving linearly at a speed of 0.45 m/s at rotational speed of 100 rpm (a), and 50 rpm (b). The rectangular window with dashed lines shows the portion of the area covered by rotating tine mechanism used for spatial analysis.](image-url)
Data analysis

For the experiment with a single tine, 3-way ANOVA was conducted to investigate the effects of three experimental factors (tine size, soil working depth and tine speed) on soil disturbance. Specifically, two types of response variables were generated for the analysis. The first response variable was the soil disturbance width, which was obtained by counting the total number of wooden cylinders classified as levels 2 to 5 in a row and multiplying it by the spacing between two adjacent cylinders (6.35 mm). This response variable represented soil disturbance due to soil failure and lateral movement of loose soil resulting in any small or large disruption of the wooden cylinders.

The weeding impact for a single tine interacting with soil is likely to be more pronounced closer to the tine than at the lateral extremes of a soil failure. The weeds closer to the tine will have higher probability of being buried, uprooted or even cut. Therefore, a second response variable was generated termed count of highly impacted simulated weeds, which was used to determine the role of different factors in high weeding capability. This variable was generated by counting the total number of wooden cylinders classified as level 5 in a row.

A 2–way ANOVA was performed for the rotating weeder experiment to analyze the impact of two factors: working soil depth and rotational speed of the tine mechanism on weeding performance. The response variable used in this analysis was the count of highly impacted simulated weeds. For the experiment with the rotating tine mechanism, highly impacted simulated weeds were those either dislodged or displaced and tilted, and thus the response variable for this analysis was the count of wooden cylinders in a row that were classified as levels 4 and 5. A 5% probability level was used for all the analyses.

The methods used in this study could be used to determine operational parameters to achieve different weeding criteria such as higher weed plant mortality, reduced crop plant
damage or a combination of both. Since the weeding criteria may change based on species of weeds and crop or vegetable plant, the analysis could be adjusted accordingly to find optimum parameters. Wooden cylinders are a lower fidelity representation of young weed plants, and methods for better modelling and simulating young weed plants biologically is a needed line of future research.

**Results and discussion**

**Single tine soil disturbance width and count of highly impacted simulated weeds**

The ANOVA analysis for soil disturbance width showed that tine diameter, working soil depth and their interaction had significant effects on soil disturbance width \((p < 0.0001)\). The \(p\)-value for tine speed was higher than the 5% significance level \((p = 0.098)\), and thus there was no evidence to support a speed effect on the disruption of the soil in the 0.23 to 0.45 m/s range. The depth and width effects on the width of soil disturbance was consistent with the studies conducted by several soil dynamics researchers. Their work focused on the development of soil force prediction models for narrow tillage tools and tines in which soil disturbance width was dependent on soil properties and the geometry of the tine, but independent of tine speeds (Godwin & Spoor, 1977; Perumpral et al., 1983; McKyes & Ali 1985).

The significant interaction between tine diameter and working soil depth suggested that soil disturbance width was affected by combinations of different levels of the two factors. The lowest soil disturbance width occurred when the 6.35 mm diameter tine was inserted into the soil at the 25.4 mm depth and was, as a mean value, 27.5 mm. The highest mean width of soil disturbance was 69.6 mm for a 9.53 mm tine at the 76.2 mm soil depth (Fig. 3.6). These results showed that the mean width of soil disturbance increased with increases in tine diameter at all three soil depths used in the experiments. Similarly, the increase in working depth also increased the mean soil disturbance width.
The trend in this experiment of changes in the soil disturbance width due to tine diameter and soil depth was consistent with the work conducted by Godwin and Spoor (1977). In their work, they showed that the ratio of forward rupture distance to tine width increases with increasing aspect ratio (soil depth/tine width) for different rake angles. Assuming soil rupture for a cylindrical tine is similar forward and sideways, the width of soil disturbance for the single tine would be about two times the forward rupture distance. Using this association between soil disturbance and forward rupture distance and the relationship between two ratios, the widths of soil disturbance would increase for the increases in depths and diameters used in the experiment based on Godwin and Spoor’s work. The experimental results were consistent with their prior work. However, it was observed that mean width did not change much for the tine with the 6.35 mm diameter at depths of 50.8 mm and 76.2 mm probably because the soil depth of 76.2 mm

Figure 3.6. The interaction effect of tine diameters and soil working depths on the width of soil disturbance. Solid dots and error bars denote means and standard deviations respectively. The mean sharing same letters are not significantly different at \( p<0.05 \) using Tukey’s adjusted comparisons.
was greater than the critical depth for the 6.35 mm tine under the test soil conditions. For depths greater than the critical depth, the soil failure mechanism changes and any increase in depth does not considerably increase the forward rupture distance or soil disturbance width (Godwin and Spoor, 1977; Godwin, 2007).

Diameter, depth and speed all had a significant effect on highly impacted simulated weed counts (P < 0.0001). The mean values of count of highly impacted simulated weeds increased as the depth increased for all three tine diameters and at both tine speeds (Fig. 3.7). Mean counts increased with increasing tine diameters at all soil depths except at the 25.4 mm depth. At a soil depth of 25.4 mm, the 7.94 mm and 9.53 mm diameter tines had almost same mean count, possibly due to higher variation of the data for 7.94 mm at this depth. For a typical soil failure profile of a single tine, soil disruption will be high closer to the tine and gradually decrease laterally. The section of the soil failure profile, close to the tine, where disruption of soil is higher and with higher weeding impact was called the effective weeding zone (Fig. 3.3). This zone increased as the width of the soil disturbance increases. Because the soil disturbance increased with increasing tine diameters and soil depths in the experiment, the effective weeding zone also increased correspondingly resulting in a relatively higher count of substantially affected simulated weeds for the two factors.

Similarly, the mean count was higher for the faster tine speed of 0.45 m/s at all three soil depths and for all three diameters of the tine. At the higher speed of 0.45 m/s, the disrupted loose soil probably gained momentum due to the fast-moving tine and thus, moved vigorously and farther away from the tine. Consequently, more simulated weeds may have been dislodged for the speed of 0.45 m/s. Interestingly, the mean count of highly impacted simulated weeds was zero for the 6.35 mm diameter tine at a depth of 25.4 mm and a speed of 0.23 m/s, although the
center simulated weed was in the path of line of action of the tine and should have been dislodged. This is probably because the loose soil that was disrupted all around the tine pushed the middle simulated weed away from the line of action of the tine as it moved. Furthermore, the soil motion was probably too slow to completely dislodge any simulated weeds.

![Graph showing interaction effects of tine diameters and working soil depths on the count of highly impacted simulated weeds for speeds of 0.23 m/s (solid line) and 0.45 m/s (dashed line).]

Figure 3.7. The interaction effects of tine diameters and working soil depths on the count of highly impacted simulated weeds for speeds of 0.23 m/s (solid line) and 0.45 m/s (dashed line).

Rotating weeding tine mechanism effective weeding width

ANOVA analysis showed the working soil depths, tine mechanism rotational speed, and their interactions all had a significant effect on the count of highly impacted simulated weeds (P < 0.05). The count of highly impacted simulated weeds was found to increase with the increases in working soil depth and rotational speed of the tine mechanism (Fig. 3.8). The count was lowest when the tine mechanism was rotated at the slowest speed of 25 rpm and the shallowest
The mean count of highly impacted weeds for these treatments was 4.2. The largest mean count of highly impacted simulated weeds was 11.9, which was observed at the speed of 100 rpm and depth of 76.2 mm.

Since the rotating mechanism consisted of four 7.53 mm diameter cylindrical tines, the soil disturbance pattern for each tine would be similar to that of a narrow tine and the width of soil disturbance would increase if the tines are inserted at greater soil depths. Because the effective weeding width also increases with the increase in width of soil disturbance, as discussed in single tine experiment, higher numbers of simulated weeds were found to be impacted at greater soil depths for all three rotational speeds.

The count of highly impacted weeds was also observed to increase for higher rotational speeds of the tine mechanism. The mean count varied marginally for rotational speeds of 25 and 50 rpm at both the soil depths; however, the variations were considerably higher when compared
to the mean count caused by the rotational speed of 100 rpm at the corresponding depths. These results suggest larger rotational speeds of the tine mechanism causes a more substantial weeding effect.

The increase in the count of highly impacted simulated weeds for higher rotational speeds was because the tine paths were closer to each other (Fig. 3.5(a)) when the mechanism was rotated at higher speeds, and therefore the mechanism disturbed a larger area of soil within the overall path of the mechanism. On the contrary, at lower rotational speeds, the tine paths were farther apart, and therefore, considerably lower numbers of simulated weeds were impacted due to a smaller soil disturbance area along the mechanism’s path of travel (Fig. 3.5(b)).

Analyzing the figures generated from simulation results showed that the percentage of maximum possible effective area of soil disturbance for all the treatments were 25.6%, 27.1% and 37.7% at 25.4 mm soil depths and 51.6%, 52.5% and 68% at 76.2 mm soil depths for the rotational speed of 25, 50 and 100 rpm respectively (Fig. 3.9). These values were calculated based on 9.3 mm and 21.6 mm effective soil disturbance width obtained for the 6.35 mm tine at 25.4 mm and 76.2 mm soil depths respectively in the single tine experiments. The experimental results from the rotating tine mechanism showed that the percentage of highly impacted simulated weeds over total number of simulated weeds within the effective width were 35 %, 41.7 % and 67.8 % at a 25.4 mm tine depth of and 52.8 %, 56.1 % and 99.4 % at a 76.2 mm tine depth for the rotational speeds of 25, 50 and 100 rpm respectively (Fig. 3.9).

At each soil depth level used in the test, the percentages increased with increasing rotational speed of the rotating tine mechanism for both cases, which suggest that the impact on the simulated weeds have direct correlation to the area of soil disturbed due to different rotating speed of the tine mechanism. Although, there is similarity in the trends of percentage at each
soil depth, the difference in the values of area percentage from the simulation did not correspond well with the count percentage from the experiments. This effect may be due to the simulation not accounting for increased kinetic energy transferred to soil particles at the higher rotation speeds. The simulation only used effective soil disturbance width around each tine path to estimate effective soil disturbance area.

Figure 3.9. Simulation results show the percentage of soil disturbance area in the maximum possible area for all the treatments, labeled area% and represented by dashed lines, compared with the percentage of possible highly impacted simulated weeds for each treatment, labeled count% and represented by solid lines, for rotational speed of 25, 50 and 100 rpm and at soil depths of 25.4 mm and 76.2 mm.

Conclusions

A controlled experimental set up and simulated weed plants were used to study the interaction between soil and a mechanical weeding tool and its potential impact on weeding performance. Based on the experiments performed in a soil bin in a controlled lab setting with simulated weed plants, following conclusions were drawn:
• The width of soil disturbance due to single narrow tine increases with increases in tine diameter and soil depth. The two speeds 0.25 m/s and 0.45 m/s used in the test had no significant effect on the width of soil disturbance. Overall, it is likely that higher percentage of weed plants would be damaged in a given area for higher tine diameter, soil depths and tine speeds.

• For rotating tine mechanism, a higher percentage of weed plants would be damaged in a given area for higher soil depths and rotational speeds.

• The effective area of soil disturbance estimated using the simulation study showed similar trends in counts of highly impacted weeds, which suggested the number of weeds damaged due to a rotating tine mechanism can also be estimated through simulation.

References


CHAPTER 4. MODELING SOIL FORCES ON A ROTATING TINE MECHANISM IN ARTIFICIAL SOIL

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Abstract

Understanding soil-tool interaction can enable better maneuvering of weeding tools to achieve higher weeding efficacy. The objective of this research was to develop and evaluate mathematical models of forces acting on a tine of a rotating tine mechanism operating at different linear and rotational velocities for studying soil-tine interaction. The kinematics associated with linear and rotational velocities of a rotating tine mechanism were modelled and the magnitude of shearing and inertial forces were estimated. Two sets of soil bin experiments were conducted using artificial soil: (i) with one tine to estimate the coefficient values and (ii) with two tines 180° apart to evaluate model performance. Experimental conditions were the same for both the sets of tests. Experimental factors were longitudinal velocity at three levels (0.09 m/s, 0.29 m/s and 0.5 m/s) and speed ratio, the ratio of longitudinal velocity to peripheral velocity of the tines, at three levels (1, 1.5 and 2). Horizontal draft force and torque on the tine mechanism were measured. A nonlinear least squares method was used to estimate model parameters from experimental data resulting shear force coefficient ranging from 2.96 to 37.5 N and inertial force coefficient ranging from 16.6 to 528 N-s²-m⁻²). These variations in shear and inertial forces on the tine were due to differences soil failure patterns across the treatments. The longitudinal and tangential forces predicted using the model with single tine parameters had trends similar to the measured forces in the two tine experiments. However, the model overestimated the predicted forces because it did not account for the reduced force on a tine due to soil disturbance created by the other tine.
Introduction

The efficacy of mechanical weed control depends on proper operation of the weeding tools. There are multiple factors that can affect the control of the weeding tools. Soil type and variability of soil conditions are among the abiotic factors that have substantial impacts on tool movement in the soil and energy consumption by the tool’s mechanism. Soil properties are typically uncertain and can vary greatly within a field, including soil textural composition, soil moisture content and soil strength and density. Since soil-to-tool interaction is dependent on such soil properties, their high variability can affect the kinematic operation and performance of mechanical weeding mechanisms. Similarly, the presence of different species of weeds and crop plants also affect control of the tools and weeding efficacy. Different weed species have different morphology and root structures, which can dictate how closely and vigorously the weeder tool should be operated to negatively impact the weeds while minimizing damage to the crop plants (Merfield, 2016).

Currently, many weeding tool designs exist for intra-row weeding such as the finger weeder, torsion weeder, brush weeder, cycloid hoe, disc hose and intra-row knife weeder (Ahmad et al., 2014; Griepentrog et al., 2006; Merfield, 2016; Pérez-Ruiz et al., 2012). The availability of multiple designs can create questions about which one should be chosen for specific weeding and crop planting situations. Furthermore, each tool requires operators to learn how to adjust the tool for different soil conditions to achieve better weed control efficacy. Generally, limited studies have been conducted on automatically-controlled mechanical/physical weeding systems, so little is known about how to systematically optimize these systems under varying soil conditions.

Studying the interaction between weeding tools and soil reactions to the operating tools can provide valuable insight into the application of tools for intra-row mechanical weeding
systems. By observing the interaction between a tool and soil, behaviors can be characterized for different tool settings. This understanding could also enable discovery of useful design guidelines and methods for optimizing the energy efficiency and control of robotic intra-row weeders.

As a specific example, a vertically rotating tine mechanism can be used for intra-row weeding. The mechanism rotates about a vertical axis and consists of multiple narrow tines vertically engaged in the soil. Weeding takes place through tine and soil/weed contact. The effect of several parameters such as tine shape, size and quantity, tine depth, and speed on weeding performance can be evaluated. Kshetri et al., (2019) studied how soil depth, longitudinal and rotational speeds affected weeding performance of the rotating tine mechanism. However, weeding performance of the mechanism also depends on how easily it can be drawn through the soil. The resistive forces from the soil can impact operation of the mechanism and thus, influence weeding efficacy. Therefore, having prior knowledge of forces on the mechanism at different operating conditions may help optimize its performance for weeding. Thus, the objectives of this research were to:

1. Explore the performance of a mathematical model in estimating soil reaction forces acting on the rotating tine mechanism, and
2. Determine how the soil reaction forces change with operating conditions.

**Background**

The soil reaction force on a narrow tine engaged in the soil is due to summation of three types of forces: (i) the force required to overcome the soil shear strength, (ii) inertial forces required to accelerate soil particles, and (iii) frictional forces at the soil-to-tool interface. Typically, the magnitude of these soil reaction forces depends on soil properties, tine geometry and tine operational parameters (Godwin & Spoor, 1977; Hettiaratchi et al., 1966; Kushwaha et
al., 1993; Mckyes, 1985). Under quasi-static states, the soil reaction force associated with soil strength is independent of tool velocity (Hettiaratchi et al., 1966; Upadhyaya et al., 1984; Wheeler & Godwin, 1996). For a slow-moving tine, the soil reaction force is primarily due to soil and tine parameters associated with shearing the soil. However, at relatively higher velocities, a higher force is required to also accelerate the soil particles in front of the tine. This inertial force increases the overall soil reaction force as the velocity of the tine is increased. Soil-to-tine frictional and adhesive forces also develop between tines and soil particles, but these forces are relatively small compared to soil shear strength and inertial forces.

For a vertical tine of a rotating tine mechanism held at fixed soil depth, the soil reaction force will mainly act horizontally to the tine in a direction opposite to the tine’s direction of motion. The rotating tine mechanism is simultaneously rotated and translated along the crop row with the movement of the vehicle. The combination of these motions causes each tine to trace curved trajectories in the soil and thus, its direction of motion and velocity will vary along its path (Kshetri et al., 2019). Likewise, the force on the tine will also be a function of its instantaneous position and velocity on its path. The kinematics of the rotating tine mechanism can be used to develop a mathematical model for estimating the draft force and torque associated with the rotating tine mechanism at various travelling and rotational velocities.

**Development of model based on kinematics of single tine of a rotating tine mechanism**

The model will be based on a rotating tine mechanism (Fig. 4.1(a)) that was designed as a weeding tool for a robotic intra-row mechanical weeder at Iowa State University (Fig 4.1(b); Gai et al., 2019). It was made up of a solid steel disc with an outside diameter of 152 mm. The disc consisted of multiple holes to mount vertical tines that engage in the soil during its operation. The holes were in a 127 mm diameter circular pattern near the edge of the disc (Fig. 4.1(a)).
For development of the model, the rotating tine mechanism was assumed to operate at constant longitudinal and rotational velocities. The tine location changes as a function of time, and soil reaction forces acting on the tine can be studied using a dotted circle (Fig. 4.2) representing the trajectory of the tine with respect to the center of the tine holder. The initial position of the tine (point A) was the right-most point when facing in the direction of travel. The location of the tine in the mechanism frame is based solely on the angle $\theta$ between the two line segments from the center of the circle (O) to the tine’s initial position (A) and to the current position on the circle ($P_x$) (Fig. 4.2).

The $V_L$ denotes longitudinal velocity of the mechanism along the positive x-axis. Assuming the tine mechanism rotates in the counterclockwise direction, the peripheral velocity of the tine, $V_P$, is tangent to the circle and has a constant magnitude, the product of the rotational velocity and the mechanism radius. The speed ratio, $\lambda$, is the ratio of peripheral to longitudinal velocity ($V_P / V_L$). Geometrically, for any angular position $\theta$ of the tine, the angle between the vectors representing $V_L$ and $V_P$ is also $\theta$.
The instantaneous velocity of a tine at any point on the circle will vary despite constant $V_L$ and $V_P$. The instantaneous velocity of a tine at any point on its path is denoted by $V_R$ and its magnitude at any angle $\theta$ can be calculated as the resultant of the longitudinal and peripheral velocities using the law of cosines as shown below:

$$V_R = \sqrt{V_L^2 + V_P^2 + 2V_L V_P \cos \theta} \quad (1)$$

Similarly, the direction of a tine’s velocity at any point on its path with angular position $\theta$ is the direction of resultant velocity vector $V_R$. If $\alpha$ is the directional angle formed by vector $V_R$ with respect to the longitudinal direction of travel, it can be calculated using:

$$\alpha = \tan^{-1}\left(\frac{V_P \sin \theta}{V_L + V_P \cos \theta}\right) \quad (2)$$

Using the relationship $\lambda = V_P / V_L$, equations (1) and (2) can be rewritten as equations (3) and (4) respectively given below:

$$V_R = \left(\sqrt{1 + \lambda^2 + 2\lambda \cos \theta}\right) V_L \quad (3)$$

$$\alpha = \tan^{-1}\left(\frac{\lambda \sin \theta}{1 + \lambda \cos \theta}\right) \quad (4)$$

The soil reaction force acting on a tine at any point on its path is denoted by $F_{\text{soil}}$. The draft force on the rotating tine mechanism will act opposite to its travelling direction. If the mechanism only has a single tine, the draft force will be equal to component of $F_{\text{soil}}$ along the longitudinal travel direction (Fig. 4.2). The longitudinal force component of $F_{\text{soil}}$ for a tine at some point on its path is represented by $F_L$ and can be expressed as follows:

$$F_L = F_{\text{soil}} \cos \alpha \quad (5)$$
The torque on the rotating tine mechanism with single tine will be equal to torque acting on the tine as it revolves in the soil. The torque on the tine can be expressed as $F_T \times R$, where $F_T$ represents the component of the soil reaction force acting along a tangent to the circle of revolution, and $R$ is radius of the circle and represents the distance between center of the rotating tine mechanism and position of the tine in the mechanism (Fig. 4.2). The direction of $F_T$ will be opposite to the direction of peripheral velocity vector $V_P$ (Fig. 4.2). The magnitude of $F_T$ can be calculated as component of $F_{soil}$ along the tangential direction. The angle between the force vectors $F_{soil}$ and $F_T$ is denoted by $\beta$. The geometry shows that $\beta$ can be replaced by absolute...
difference between $\theta$ and $\alpha$ (i.e. $|\theta - \alpha|$). Therefore, the tangential force component of the soil force on a tine at any position can be given by:

$$F_T = F_{soil} \cos(|\theta - \alpha|)$$

(6)

Since soil reaction force is the summation of shearing, inertial and soil-to-tool forces, $F_{soil}$ can be broken into its components and expressed as:

$$F_{soil} = F_{shearing} + F_{inertial}$$

(7)

where $F_{shearing}$ and $F_{inertial}$ are shearing and inertial force components of soil reaction force respectively. Because soil-to-tool friction force is typically small compared to shearing and inertial forces, it was assumed to be negligible.

Analytical force prediction models have been developed for narrow tines, which show how the two shearing and inertial forces relate to soil properties and conditions, tine geometry and tine operating conditions. According to these models, approximation of the shearing force depends exclusively on soil strength and properties, soil working depth, and tine width (Hettiaratchi et al., 1966; McKyes & Ali, 1977; Perumpral et al., 1983; Wheeler & Godwin, 1996). The inertial force, on the contrary, is a function of tine velocity in addition to soil and tine parameters (Upadhyaya et al., 1984; Mckyes, 1985; Swick & Perumpral, 1988; Wheeler & Godwin, 1996). To separately analyze the effect of soil, tine and operating conditions on soil reaction forces, equation (7) can be replaced by equation (8) using constant terms $K_S$ and $K_I$. The expression in equation (8) has a form similar to dynamical force predicting models developed by several researchers (Upadhyaya, 1984; Mckyes, 1985; Wheeler & Godwin, 1996) for a tool with significant speed effects.

$$F_{soil} = K_S + K_I \times V_R^2$$

(8)
where coefficient $K_S$ captures the effects of soil and tine properties that are associated with the shearing force, while $K_I$ accounts for the properties associated with the inertial force. Substituting the expression for $F_{soil}$ (equation (8)) in equations (5) and (6), and expanding the subsequent equations further results in the following two equations for longitudinal and tangential forces, respectively.

\[
F_L = (K_S) \cos \alpha + (K_I \times V_R^2) \cos \alpha \\
F_T = (K_S) \cos(|\theta - \alpha|) + (K_I \times V_R^2) \cos(|\theta - \alpha|)
\]

**(Effects of tine kinematics on longitudinal and tangential forces)**

Since angular position $\theta$ is periodic, the size and direction of the tine velocities and forces in equation (1) to (10) also repeat periodically through each revolution for constant longitudinal and rotational velocities. Therefore, analysis of one revolution is sufficient to examine the effect of tine kinematics on the forces because the effects will be repeated in subsequent revolutions. The speed ratios ($\lambda$) of 1, 1.5 and 2 were chosen based on the following considerations. Speed ratios of 1 and greater are advantageous for mechanical weeding. At a speed ratio of 1, each tine comes to a stop and the soil reaction force on goes to zero at the left-most point in its trajectory. For speed ratios greater than 1, the tine trajectory has loops with soil reaction forces transitioning to being in the same direction as the longitudinal motion. Thus, with speed ratios greater than 1, the tine mechanism can facilitate weeding through more soil disturbance in this part of the trajectory. Additionally, because of the direction of the reaction force, total draft force will be lower while the torque increases.

The kinematic model was used to analyze the magnitude and angle of the resultant tine velocity, $V_R$, as a function of angular position ($\theta$) for longitudinal velocity $V_L$ of 0.5 m/s at three
test speed ratios (Fig. 4.3(a)). For all three speed ratios, the resultant tine velocity magnitude was highest at $\theta = 0^\circ$. At this point, $V_P$ and $V_L$, are in the same direction, and therefore, the resultant velocity magnitude will be the simple sum of two component velocity magnitudes. The magnitude decreases to a minimum at $\theta = 180^\circ$. At this position when the speed ratio was 1, the tine had a resultant zero velocity because the component velocities were equal and opposite. The profiles of the resultant velocities at three speed ratios were similar for different longitudinal velocities; however, their magnitude varied across $\theta$ and were proportional to the longitudinal velocity.

The angle of the resultant velocity, $\alpha$, was similar for speed ratios of 1.5 and 2 (Fig. 4.3(b)). For a speed ratio of 1, $\alpha$ gradually reached $90^\circ$ at $\theta$ of $180^\circ$, where the tine was stationary. At this point, the tine resultant velocity vector is pointed to the left (along the positive $y$-axis in Fig. 4.2). However, as soon as $\theta$ increased beyond $180^\circ$, it instantaneously changed direction to the right ($\alpha = 270^\circ$). Since $\alpha$ is independent of longitudinal velocity (equation (5)), the values of $\alpha$ across $\theta$ will be same for any speed ratio irrespective of the longitudinal velocity.

![Figure 4.3](image.png)

*Figure 4.3. Resultant tine velocity magnitude (a) and angle (b) through one revolution at speed ratios 1, 1.5 and 2 for longitudinal velocity of 0.5 m/s. The profiles of resultant velocity will be similar for different longitudinal velocities but with different values. The profiles of the directional angle will be same for any longitudinal velocity with same speed ratio.*
The contribution of the shearing force and inertial force components on longitudinal force \((F_L)\) and tangential forces \((F_T)\) were studied separately to understand how tine velocity affect the two forces. The analysis was performed by evaluating equation (9) and (10) at different angular position \(\theta\) of a tine and assuming coefficients \(K_S\) and \(K_I\) to both be one.

For a speed ratio of 1, the longitudinal force component due to shearing gradually decreased to zero at \(\theta\) of 180° and increased when the tine position was at 0° (Fig. 4.4(a)). Similar trends can be observed for speed ratios of 1.5 and 2; however, the shearing force components became negative over the interval of tine position between point P2 and P4 on the circle in Fig. 4.2. The negative force implies the direction of force on the tine will be same as that of the longitudinal velocity of the vehicle. Similar trends in magnitude of the force across the angular position \(\theta\) was observed for the inertial component of the longitudinal force (Fig. 4.4(b)). However, the inertial force magnitude was affected by resultant velocity, which was also varying across tine positions (Fig. 4.3(a)).

![Figure 4.4](image-url)
Similar analysis was performed for the tangential force across the range of speed ratios. The tangential force component due to shearing (Fig. 4.5(a)) decreased to zero at $\theta$ of $180^\circ$ for a speed ratio of 1. However, the shearing force components remained relatively high for speed ratios of 1.5 and 2 throughout a revolution. The inertial force components decreased for $\theta$ values that were close to $180^\circ$, while the components increased for $\theta$ values near $0^\circ$. Unlike longitudinal force, the tangential force will not have negative force components for speed ratios greater than 1. Therefore, the tangential forces for these cases will be greater than zero.

![Figure 4.5. The tangential force component due to shearing (a) and inertia (b) on a tine as function of rotational angle ($\theta$) across three speed ratios.](image)

**Determination of coefficients $K_S$ and $K_I$**

The similarity of equations (9) and (10) with dynamical force predicting models found in literature suggests the shearing force ($K_S$) and inertial force ($K_I$) coefficients will exclusively depend on soil properties and conditions, tine geometry and operating conditions. One implication of this is, if soil properties, tine geometry and tine operating parameters are known, it is possible to estimate $K_S$ and $K_I$ and evaluate longitudinal and tangential forces on a tine based on equations (9) and (10). Most of the dynamical models have been developed for narrow tines travelling along a straight line. Moreover, the models were based on underlying patterns of soil
failure (or disturbance) and uniformity of soil mechanical properties for the tine moving along a straight line (Shen and Kushwaha, 1998). On the contrary, the tine of the mechanism move along a curved trajectory when operating in the soil. Therefore, the coefficients for different settings were evaluated from the experiments.

**Materials and methods**

**Soil bin experiments**

Two experiments were conducted in an artificial soil in a linear soil bin that was approximately 3000 mm long by 320 mm wide by 380 mm deep (Fig. 4.6). The artificial soil was composed of sand, clay, and mineral oil with a cohesion of 10 kPa and an internal friction angle of 33° as measured in a direct shear test (ASTM D3080, 2011). Before each experimental trial, the artificial soil was processed to achieve uniform conditions across the trials. The soil was first tilled with a rake to a depth of 100 mm. The soil was then bladed to achieve a uniform soil level. After leveling, the soil was compacted using a 254 mm diameter rolling cylinder with added static weight to adjust the compaction force on the soil. The compaction process took place in three steps. Each step consisted of three roller passes, where each roller pass represented forward and backward motion of the roller along the soil bin. In the first step, the soil was compacted with three roller passes without any weights. This step was followed by three roller passes with added weight of 4.5 kg. In the third step, the soil was compacted using 11.3 kg of weight in three roller passes.
Experimental apparatus

The experiments were conducted using a rotating tine mechanism (Fig. 4.1(a)). Cylindrical tines, 6.35 mm in diameter, were used in the experiments. The first set of experiments were conducted with one tine, while the second set was conducted using two tines mounted 180° apart from each other.

The mechanism was rotated using a DC motor (Ampflow F30-150, Powerhouse Engineering Inc., Belmont, CA). A 20:1 inline gearbox (AE090, Apex Dynamics, Ronkonkoma, NY) was mounted between the DC motor and the rotating tine mechanism to increase torque capacity of the system and overcome possible large resistive torque from the soil when the mechanism is spinning. The mechanism was rotated at desired rotational speeds by controlling the DC motor using a PID controller. A rotary torque transducer with an integrated rotary
encoder (torque rated capacity of 100 N-m, model T4, Interface Inc., Scottsdale, AZ) was used to measure torque and rotational speed of the mechanism. The rotating tine mechanism, DC motor, gearbox, torque transducer and other additional parts were assembled and were mounted to a structure fabricated from extruded aluminum members (Fig. 4.6). The framework was mounted to the tool carriage on the soil bin that was moved longitudinally with a belt winch attached to a gear motor (BLS6400-GFS, Oriental Motor Co., LTD., Japan). Three three-axis force transducers (TR3D-A, Michigan Scientific Corp., Charlevoix, MI) on the tool carriage system were used for measuring soil reaction forces on the tine mechanism as it was moved through the soil. The data was acquired with a data logger (DEWE-43A, DEWESoft, Slovenia) and samples of each channel were acquired at a 100 Hz sampling frequency.

**Experimental Design**

A Completely Randomized Design (CRD) of experiments was used for both experiments with one tine and two tines. The same experimental procedure was used for both experiments. The working soil depth in the experiment was 70 mm. The rotating tine mechanism was operated at three longitudinal velocities and three speed ratios. The three levels of longitudinal velocity were 0.09 m/s, 0.29 m/s, and 0.5 m/s, and the three speed ratios were 1, 1.5 and 2. These resulted in the tine mechanism being rotated at nine different speeds ranging from 14 to 149 rev/min (1.47 to 15.6 rad/s) to achieve the three speed ratios at different levels of longitudinal velocity.

The combination of three levels of longitudinal velocity and speed ratios resulted in nine treatment levels. Each treatment was replicated three times and thus, a total of 27 (9 X 3) experiment trials were conducted for both tests.

**Data Analysis**

The torque and longitudinal force measurements used for data analysis tended to have a sinusoidal appearance (Fig. 4.7). The analysis was conducted only along the steady state section
of the measured values. The torque was converted to tangential force by dividing torque values by \( R \), where \( R \) was equal to 0.0635 m. The modeled longitudinal and tangential forces developed for single tine, shown in equations (9) and (10), were then fit to the measured longitudinal and tangential force measurements using a nonlinear least-squares method (lsqnonlin) in MATLAB (The MathWorks Inc, Natick, MA). Initial points of the measured data were manually selected to match the phase shift of the models. The nonlinear least-squares method computed the coefficients \( K_S \) and \( K_I \) by solving expression of the form

\[
\min_{K_S, K_I} \left( \| (F_{L, measured} - F_L) \|^2_2 ; \| (F_{T, measured} - F_T) \|^2_2 \right)
\]

(11)

where \( F_{L, measured} \) is measured longitudinal force, \( F_{T, measured} \) is measured tangential force, and \( F_L \) and \( F_T \) are the modeled forces. The minimization (equation (11)) was performed across \( \theta \) corresponding to intervals with data from at least two revolutions of the mechanism. The coefficients \( K_S \) and \( K_I \) were estimated for all trials of the experiment with a single tine. ANOVA was conducted to compare \( K_S \) and \( K_I \) across the nine treatment levels using speed ratio and longitudinal velocity as factors.

The efficacy of the kinematic model was analyzed by comparing longitudinal and tangential forces measured in the second experiment with corresponding forces predicted using the models for two tines. The forces on the two tines were estimated by summing individual forces on each tine that were \( 180^\circ \) apart computed using the model over a revolution.

**Results and Discussion**

The profiles of the two measured forces were consistent with the profiles predicted by the model. Specifically, for a speed ratio of 1, the longitudinal and tangential forces went to zero at \( \theta = 180^\circ \), which matched the prediction based on the model (Fig. 4.7 (top row)). The experimental results for longitudinal and tangential forces also matched the model for the other speed ratios.
For instance, longitudinal forces were negative (in the direction of travel) near $\theta = 180^\circ$, and tangential forces were greater than zero throughout the tine’s revolution (Fig. 4.7 (middle row) and (bottom row)). The forces generally followed these patterns for all treatments (see Figure 4.7 for 0.09 m/s and Appendix for 0.29 m/s and 0.5 m/s).

Figure 4.7. Comparison between the measured and modeled longitudinal and tangential forces for longitudinal velocity of 0.09 m/s and speed ratios of 1 (top row), 1.5 (middle row) and 2 (bottom row).
The ANOVA for $K_S$ (Table 4.1) showed speed ratio and interaction between longitudinal velocity and speed ratio had significant effects on $K_S$, while there was no evidence to support effect of longitudinal velocity on $K_S$. Similarly, ANOVA for $K_I$ (Table 4.2) showed longitudinal velocity, speed ratio and their interaction had significant effects on $K_I$. Tukey’s HSD test at 5% significance level was used to determine treatment mean groupings (Table 4.3).

**Table 4.1. ANOVA for $K_S$**

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>Sum of squares</th>
<th>F value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal velocity</td>
<td>2</td>
<td>24.2</td>
<td>2.3374</td>
<td>0.1252</td>
</tr>
<tr>
<td>Speed ratio</td>
<td>2</td>
<td>4977.8</td>
<td>480.4611</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Longitudinal velocity*Speed ratio</td>
<td>4</td>
<td>68.2</td>
<td>3.289</td>
<td>0.0344</td>
</tr>
</tbody>
</table>

**Table 4.2. ANOVA for $K_I$**

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>Sum of squares</th>
<th>F value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal velocity</td>
<td>2</td>
<td>513914</td>
<td>237.41</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Speed ratio</td>
<td>2</td>
<td>146195</td>
<td>67.537</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Longitudinal velocity*Speed ratio</td>
<td>4</td>
<td>179113</td>
<td>41.37</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

**Table 4.3. Mean, standard deviation (sd) and groupings based on Tukey’s HSD test for nine treatments**

<table>
<thead>
<tr>
<th>Longitudinal velocity</th>
<th>Speed Ratio ($\lambda$)</th>
<th>$K_S$ (N) mean</th>
<th>sd</th>
<th>Groupings</th>
<th>$K_I$ (N.s²/m²) mean</th>
<th>sd</th>
<th>Groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>1</td>
<td>31.3</td>
<td>1.98</td>
<td>b</td>
<td>77.7</td>
<td>85.5</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>6.32</td>
<td>0.5</td>
<td>a</td>
<td>528</td>
<td>17.4</td>
<td>c</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.96</td>
<td>2.04</td>
<td>a</td>
<td>389</td>
<td>44.6</td>
<td>b</td>
</tr>
<tr>
<td>0.29</td>
<td>1</td>
<td>34.6</td>
<td>0.91</td>
<td>b</td>
<td>16.6</td>
<td>5.7</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>8.93</td>
<td>0.82</td>
<td>a</td>
<td>75.6</td>
<td>2.02</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.02</td>
<td>1.3</td>
<td>a</td>
<td>57.9</td>
<td>2.59</td>
<td>a</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>37.5</td>
<td>4.43</td>
<td>b</td>
<td>21.2</td>
<td>4.89</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>5.26</td>
<td>2.59</td>
<td>a</td>
<td>42.8</td>
<td>6.93</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.96</td>
<td>2.96</td>
<td>a</td>
<td>23.2</td>
<td>4.37</td>
<td>a</td>
</tr>
</tbody>
</table>
The mean values of $K_S$ were higher at the speed ratio of 1 for all three levels of longitudinal velocity. The means of $K_S$ at speed ratio 1 for longitudinal velocities 0.09, 0.29 and 0.5 were 31.3 N, 34.6 N and 37.5 N respectively and were all placed in the same group (b) based on Tukey’s HSD. At speed ratios 1.5 and 2, the mean values of $K_S$ were lower and were placed in the same group for all three longitudinal velocities. Similarly, the means of $K_I$ were higher for longitudinal velocity of 0.09 m/s at 528 N.s$^2$/m$^2$ and 389 N.s$^2$/m$^2$ for speed ratios 1.5 and 2 respectively. All other $K_I$ estimates were placed in the same Tukey group.

**Discussion of the $K_S$ and $K_I$ coefficients**

The differences in the coefficients could be attributed to different trajectories, patterns of soil disturbance and soil behavior resulting from different longitudinal velocities and speed ratios associated with the treatments. In the experiment, the tine moved in three distinct trajectories depending on the speed ratios (Fig. 4.8). The trajectories consisted of loops between two curved tine paths. The distances between two successive loops were identical for same speed ratio irrespective of longitudinal velocity but decreased with increasing speed ratios. The trajectories at speed ratios 1.5 and 2 consisted of loops, with speed ratio 2 having a larger loop, while the trajectory at a speed ratio of 1 did not create any loops. The soil disturbance lateral to the trajectories appeared to vary with longitudinal velocities across different treatments. The soil failure tended to be on the right side of the curved tine trajectory for longitudinal velocities 0.29 m/s and 0.5 m/s, while a narrow soil disturbance occurred on both sides of the trajectory for a longitudinal velocity of 0.09 m/s. Moreover, the soil disturbance zone on the right side of the trajectory, for longitudinal velocities of 0.29 m/s and 0.5 m/s, was observed to be wider with increasing speed ratios.

The trajectories and widths of soil disturbance can impact shearing and inertial forces on a tine. A soil disturbance created by a tine moving along a curved trajectory could partially or
completely intersect with soil disturbance previously created by the tine. The extent of intersection can influence the magnitude of forces required to shear the soil or accelerate soil particles by changing properties or behavior of the soil interacting with the tine.

The soil failures by a tine in the experiment were found to intersect substantially for speed ratios 1.5 and 2 in the loops formed along its trajectory. When looping, lower shearing force may be required for the tine to cut a smaller portion of the soil in an area which was disturbed. Therefore, the coefficients, $K_S$, associated with shearing force were smaller for speed ratios 1.5 and 2 (Table 4.3) than for speed ratio 1, which did not create any loops. The soil disturbances also impacted inertial force by changing soil properties along different sections of the tine’s path. However, the inertial force was also dependent on velocity of the tine along its trajectory. Therefore, $K_I$ for the treatments (Table 4.3) account for the inertial forces based on tine velocity and changing soil properties due to variation in soil disturbances observed for different experimental settings.

**Evaluating models for two tines**

The values of $K_S$ and $K_I$ corresponding to different treatments in Table 4.3 were used in the model to predict forces on the two tines for different experimental treatments. Separate coefficients were used for different treatments even though the coefficients were categorized into small set of distinct groupings because each pair of $K_S$ and $K_I$ associated with the treatment captured unique soil failure and resulting dynamics on the tine for the treatment. Using coefficients in the models based on groupings could have resulted in loss of information due to difference in soil failure and its impact on forces on the tines for different treatments. The magnitudes of both measured and predicted forces were found to oscillate (Fig. 4.9), therefore, analysis was performed by particularly comparing mean values of the forces obtained from the two methods.
Figure 4.8. Soil disturbances caused by single tine moving in artificial soil for different treatments. (Top row) Soil disturbances for $\lambda = 1$ and (a) $V_L = 0.09$ m/s, (b) $V_L = 0.29$ m/s, (c) and $V_L = 0.5$ m/s. (Middle row) Soil disturbance for $\lambda = 1.5$ and (d) $V_L = 0.09$ m/s and (e) $V_L = 0.5$ m/s. (Bottom row) Soil disturbance for $\lambda = 2$ and (f) $V_L = 0.09$ m/s and (g) $V_L = 0.5$ m/s.
The means of measured and predicted longitudinal forces decreased with increases in speed ratios for all three levels of longitudinal velocities (Fig. 4.10(a)). This observation indicated the model was able to capture decreasing trend of the longitudinal force on two tines in the experiment that was observed when analyzing the kinematics.

However, magnitudes of the predicted mean forces were higher than the measured values. The models overestimated the forces probably because the models did not account for soil disturbance that occurred during the operation in an experiment. During the operation, the tines moved in the soil disturbed by each other at different points along their path. As a result, the force on individual tine could have diminished due to reduced shearing and inertial effects of the disturbed soil operating under the same experimental condition.

The tangential forces increased with speed ratios at all three levels longitudinal velocities except at longitudinal velocity of 0.09 m/s and speed ratios of 1.5 and 2 (Fig. 4.10(b)). For these two treatments, the measured tangential forces were almost identical. The profiles of predicted
tangential forces tended to be increasing and parallel with trends of the forces between different speed ratios measured in the experiment for most cases. Similar to the result for longitudinal force, the magnitudes of predicted tangential forces overestimated the measured values because the model did not capture soil failure which would reduce the forces on the tines.

![Comparison between measured and predicted forces](image)

**Figure 4.10.** Comparison between means of the measured (meas.) and predicted (pred.) longitudinal (a) and tangential (b) forces for different longitudinal velocities and speed ratios used in the experiment.

**Conclusions**

From this research, we can conclude:

- The shearing and inertial coefficients, which capture force magnitude resulting from soil-tine interactions varied among different treatments due to difference in patterns of soil failure.

- Longitudinal and tangential forces estimated using the model matched patterns of the respective forces measured for two tines at different experimental treatments. However, magnitudes of the estimated forces were higher than measured forces because the models did not account for the soil failure.
References


ASAE Standards, 46 Ed. (1999a). S313.3. Soil cone penetrometer. ASAE, St Joseph, MI.

ASAE Standards, 46 ED (1999b). EP542. Procedures for using and reporting data obtained with the soil cone penetrometer. ASAE, St Joseph, MI.


CHAPTER 5. INVESTIGATING EFFECTS OF ROTATIONAL AND LINEAR VELOCITIES OF A VERTICAL ROTATING TINE MECHANISM ON SOIL REACTION FORCES FOR FIELD CULTIVATION

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Abstract

Studying soil-tool interaction can provide valuable information on actuation and energy requirements of a weeding tool operating in soil. Soil-tine interaction was investigated for a vertical rotating tine mechanism that was intended to be used as a weeding mechanism for an automated mechanical intra-row weeder. The main objective of the research was to investigate the effects of linear and rotational velocities on soil reaction forces and power associated with actuation of the rotating tine mechanism in soil. A series of soil bin experiments were conducted in loam soil. Soil horizontal (draft) force and torque on the mechanism were tested for three longitudinal velocities of 0.09 m/s, 0.29 m/s and 0.5 m/s that were used to move the mechanism linearly across the soil bin length. Speed ratio, defined as the ratio of the longitudinal velocity to peripheral velocity of the rotating tines, determined the rotational speeds required for the study. The draft force and torque were evaluated at four levels of the speed ratio (0, 1, 1.5 and 2).

Analysis of Variance (ANOVA) was performed for statistical analysis using p < 0.05. Power was calculated using draft force and torque measurements from different experimental settings. Both longitudinal velocity and speed ratio had significant main and interaction effects on the draft force and torque. In most cases, the draft force decreased, while torque increased with increasing speed ratios for different longitudinal velocities used in the study. The study showed that linear and rotational velocities of the rotating tine mechanism can be optimized to achieve sufficient soil disturbance for weed control while operating within the limitations of the power source.
Introduction

Weed control is important for producing high yield and high-quality grain and vegetable crops. Currently, weeds are typically controlled using herbicides, although other methods can be used such as manual, chemical, mechanical, biological, and thermal weed control. Among these, mechanical weed control is a widely used, non-chemical method for controlling weeds. This approach has recently gained increased attention due to growing demand for organic food production, environmental concerns, and emergence of herbicide resistant weeds (Griepentrog et al., 2006; Pérez-Ruiz et al., 2012; Slaughter et al., 2008; Young et al., 2014).

Innovations in different areas of technology have been integrated to automate mechanical weeding. By minimizing human intervention, automation can reduce operating time, cost and health risks associated with human labor in mechanical weeding (Pérez-Ruiz et al., 2012). Technology developed for this application such as computer or machine vision, mapping and image processing have enabled detection and separation of weed plants from crop plants. Similarly, research and development of autonomous vehicles and precision weeding tools could eliminate the need of operators and achieve efficacious weed control.

Despite these advances, the development of automated intra-row weeding technology continues to be challenging. In intra-row weeding, the weed plants that need to be controlled are near or between the crop plants. Because of the close proximity of the weeds to the crop plants, it is often difficult for the automatic machines to kill or damage the weeds without affecting the crop plants. One such challenge, among several others in intra-row mechanical weeding, is the controlled kinematic motion of weeding tools and their interaction with the soil to precisely target the weeds.

There are numerous weeding tool designs such as the finger weeder, torsion weeder, brush weeder, cycloid hoe, disc hose and intra-row knife weeder that are used for intra-row
weeding (Ahmad et al., 2014; Griepentrog et al., 2006; Merfield, 2016; Pérez-Ruiz et al., 2012). Some of these tools are passive, which are simply pulled through the soil without any extra energy input, while others are active requiring energy for active motion control. For both active and passive tools, operational settings and tool design can impact weeding efficacy. Selection of proper settings for the active tool can minimize the energy input for the actuation yet achieving good weeding performance. Energy requirements are determined by soil resistance forces acting on the tool, and the amount of weed damage depends on soil disturbance resulting from tool interaction with specific design at given settings. Since a study of soil and tool interaction includes soil disturbance and forces on the tool, exploring the interaction can provide valuable insight into the application of the tool for intra-row mechanical weeding systems.

A vertically rotating tine weeding mechanism is another design that can be used for intra-row weeding. The mechanism rotates about a vertical axis and consists of multiple narrow tines vertically engaged in the soil. Weeding takes place through contact between the tines and soil or weeds. The effect of several parameters such as shape, size and number of tines, working soil depth, linear and rotational speeds on weeding performance can be evaluated. Kshetri et al. (2019) studied how soil depth, longitudinal and rotational speeds affected weeding performance of the rotating tine mechanism. The linear and rotational speeds can also affect energy requirements for the weeding mechanism. The vertical rotation, effective for weeding through uprooting, cutting and burying, can also impact the force on the mechanism during active or passive motion. Therefore, determining linear and rotational speed effects on draft force and torque on the rotating tine mechanism could be valuable, particularly for optimizing settings for minimum energy while still achieving higher weeding efficacy.
The objective of this research was to study the effects of longitudinal velocity and rotational velocity on soil reaction forces and power for actuation of a rotating tine mechanism in soil. The specific objectives were to investigate 1. horizontal soil draft force and soil resistance torque, and 2. power required to move the mechanism at different settings of longitudinal velocities and speed ratios in loam soil.

**Materials and methods**

**Soil information**

The experiments were performed in a linear soil bin (Fig 5.1) that was approximately 3000 mm long, 320 mm wide and 380 mm high. The soil bin was filled with a loam soil (33.3 % sand, 45.2 % silt and 21.5 % clay) in a 1066 mm long section of the soil bin. The soil was initially processed by screening a field loam soil from a Clarion loam soil series (fine loamy, mixed, mesic Typic Hapludoll) according to USDA soil classification) through a 4.75 mm ASTM size screen and mixed with water to achieve an equilibrated soil moisture content of 10% (dry basis, d.b.) according to Tekeste et al. (2019) and Ghorbani (2019). Clarion soil series are common soil types on field experimental plots of the Agricultural and Agronomy Experimental Research Farm at Iowa State University in Boone, Iowa.

**Soil preparation**

Soil preparation included roto-tilling, leveling and compaction before the start of each experimental trial to maintain consistent soil conditions throughout the experiment. The soil was tilled with a portable roto-tiller (LGC120, Black+Decker, Towson, MD) to a depth of 100 mm. The soil was then bladed to create a uniform level. The soil depth in the soil bin after leveling was 205 mm. The soil was compacted using a 254 mm diameter rolling cylinder with added static weight to adjust the compaction force on the soil. The added weight was obtained using steel plates, each weighing 11.3 kg. The compaction process took place in three steps. Each step
consisted of a number of roller passes, where each roller pass represented forward and backward motion of the roller along the soil bin. In the first step, the soil was compacted with three roller passes without any weights. This step was followed by the soil being compacted with the roller and an additional 11.3 kg weight with three roller passes. In the third step, 22.6 kg of weight was added to the roller compactor which was rolled over two forward-backward passes.

Figure 5.1. Soil bin with aluminum framework supporting assembly of components attached to the rotating tine mechanism. The tool carriage system consists of load-cell instrumented plate to which the rotating tine structure was attached. Both the rotating tine mechanism and tool-carriage system can move longitudinally across the soil bin using electric motor drive system.

Experimental apparatus information

The rotating tine mechanism used in the experiment was a weeding tool, which affected weeds by disturbing the soil through the rotation of a horizontal steel disc with four tines about a vertical axis. The disc had a 152.4 mm outside diameter and cylindrical tine diameter was 6.35 mm. The tines were equally spaced around a 127 mm diameter circle. This mechanism was
developed as a part of an automatic intra-row mechanical weeder project at Iowa State University (Fig. 5.2 (b); Gai et al., 2019).

Figure 5.2. (a) Rotating tine mechanism consisted of a horizontal plate with for vertical tines and (b) the prototype of automatic intra-row mechanical weeder with two tine mechanisms on either side of a crop row.

The tine mechanism was rotated using a DC motor (Ampflow F30-150, Powerhouse Engineering Inc., Belmont, CA). A 20:1 inline gearbox (AE090, Apex Dynamics, Ronkonkoma, NY) was mounted between the DC motor and the rotating tine mechanism to increase the torque capacity of the system and overcome possible large resistive torque from the soil when the mechanism was spinning. The mechanism was rotated at desired rotational speeds by controlling the DC motor using a PID controller. A rotary torque transducer with an integrated rotary encoder (torque rated capacity of 100 N-m, model T4, Interface Inc., Scottsdale, AZ) was used to measure torque and rotational speed of the mechanism. The rotating tine mechanism, DC motor, gearbox, torque transducer and other additional parts were assembled and were mounted to a structure fabricated from extruded aluminum members (Fig. 5.1). The framework was mounted to the tool carriage on the soil bin that was moved longitudinally with a belt winch attached to a
gear motor (BLF6400-GFS, Oriental Motor Co., LTD., Japan). Three three-axis force
transducers (TR3D-A, Michigan Scientific Corp., Charlevoix, MI) on the tool carriage system
were used for measuring soil reaction forces on the tine mechanism as it was moved through the
soil. Data was acquired with a data logger (DEWE-43A, DEWESoft, Slovenia), and samples of
each channel were acquired at a 100 Hz sampling frequency.

**Experimental Design**

A Completely Randomized Design (CRD) of experiments was used for the soil bin tests.
In the experiment, the rotating tine mechanism was rotated and moved longitudinally along the
length of the soil bin. The working soil depth for tines of the rotating mechanism was 70 mm. In
the experiment, horizontal draft force and torque were investigated at different longitudinal
velocities and speed ratios. The three levels of longitudinal velocity were 0.09 m/s 0.29 m/s and
0.5 m/s. The longitudinal velocity of 0.5 m/s was the highest velocity that could be achieved with
the gear motor used in the soil bin. Speed ratio, defined as a ratio of peripheral tine velocity due
to rotation to longitudinal velocity of the rotating tine mechanism, determined the rotational
speeds of the mechanism for the tests. Four levels of speed ratio used in the experiments were 0,
1, 1.5 and 2. At speed ratio of 0, the mechanism was pulled longitudinally along the soil bin with
zero rotational speed. To achieve any constant speed ratio of 1, 1.5 or 2, the mechanism had to
be rotated at three separate rotational speeds for three different levels of longitudinal velocities
used in the experiments. As a result, there were nine different rotational speeds of the
mechanism, three for each non-zero ratio settings, ranging from 14 to 149 rev/min (1.47 to 15.6
rad/s). At a constant speed ratio, a tine of the mechanism will trace a distinct trajectory in the soil
irrespective of the longitudinal velocity. Therefore, speed ratio was selected to investigate soil
resistance forces and power across tine trajectories that can be achieved with different
combination of longitudinal and rotational velocity settings. For the mechanism, speed ratios
greater than 1 can be more advantageous for mechanical weeding because higher speed ratios can damage more weeds due to higher rotational speed. In the research, speed ratios 1, 1.5 and 2 were chosen to capture possible trends in the variation of draft forces and torques at the lower levels of the speed ratios that are favorable for weed control.

There were 12 combinations of treatment factors and levels. With each treatment replicated five times, a total of 60 (12 X 5) soil bin experiments were conducted. Soil samples were collected from six randomly selected tests to determine soil moisture content and soil bulk density. The soil moisture content was measured using an industrial oven according to ASTM D4318. From the tests, the mean soil moisture content (d.b.) and soil bulk density were 10.5% (standard deviation of 0.2%) and 1202 kg/m³ (standard deviation of 34 kg/m³) respectively. In addition to this, a cone penetrometer (FieldScout SC 900, Spectrum Technologies Inc., Aurora, IL) was used to measure the cone penetration resistance of the prepared soil according to ASABE standards (ASAE S313.3, 1999 and ASABE EP EP542, 1999). The measurements were randomly taken from 15 experimental trials. The soil cone index was observed to be relatively constant in the 75-100 mm depth range where the mean of the cone index value was 267 kPa (standard deviation of 53 kPa) with a 95% confidence interval of 251 kPa to 283 kPa.

**Data Analysis**

Analysis of Variance (ANOVA) was conducted to examine the statistical significance of the two experimental factors on soil draft force and torque acting on the rotating tine mechanism at 5% significance level. The draft force and torque measurements had transient and steady state values corresponding to changing and constant longitudinal and rotational velocities along the longitudinal section of the soil. The median values of the draft force and torque along the steady state section of the measurements were used for analysis. The median was used because it is more robust to impact of potential outliers in the data. The initial and latter transient data during
the acceleration and deceleration of the mechanism was removed for the data analysis. Tukey’s HSD was conducted at a 5% level to compare the means of the treatments for both draft force and torque. The power associated with the draft force required to pull the rotating tine mechanism longitudinally across the soil bin and that to rotate of the mechanism in the soil were theoretically calculated. The total power for different experimental settings was calculated by summing the power associated with draft force and rotation of the mechanism.

Results and discussion

Draft Force

ANOVA results showed longitudinal velocity, speed ratio and their interaction had significant statistical effects on the draft force (Table 5.1). For most cases, the draft forces decreased with increasing speed ratios for all three levels of longitudinal velocity (Fig. 5.3). The draft forces at speed ratio of 0 were relatively higher than at other speed ratios. At the speed ratio of 0, the maximum mean draft force was 124 N (standard deviation of 8 N) for longitudinal velocity of 0.5 m/s, and the draft forces at 0.09 m/s and 0.29 m/s were not significantly from each other. The lowest mean draft force was 37.2 N (standard deviation of 3.56 N) obtained with a tool speed ratio of 2 and a longitudinal velocity of 0.09 m/s. At ratios of 1, 1.5 and 2, the means of draft forces were relatively higher for higher levels of longitudinal velocity.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean of squares</th>
<th>F value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal velocity</td>
<td>2</td>
<td>4657</td>
<td>2329</td>
<td>61.795</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Speed ratio</td>
<td>3</td>
<td>30427</td>
<td>10142</td>
<td>269.15</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Longitudinal velocity*Speed ratio</td>
<td>6</td>
<td>1471</td>
<td>245</td>
<td>6.506</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
The draft force on the rotating tine mechanism is the summation of the longitudinal soil reaction forces on four tines of the mechanism acting opposite its travel direction. For speed ratio of 0, the longitudinal force on each tine is same as the soil reaction force acting on a tine along a straight line. The experimental results showed that draft forces were almost identical for longitudinal velocities of 0.09 m/s and 0.29 m/s at speed ratio of 0. This was probably because the soil reaction force was largely due to identical shearing force required to cut the soil owing to constant soil properties, working depth and tine diameter, while inertial forces due to these velocities may have been negligible. According to Schuring and Emouri (1964), inertial force becomes significant above a critical velocity given by $\sqrt{5gw}$, where $g$ is acceleration due to gravity and $w$ is width of the tine (Godwin, 2007). Based on this expression, the critical velocity for the tine used in this study was 0.56 m/s. The longitudinal velocity of 0.5 m/s is close to the critical velocity, which may have resulted in higher contribution of inertial force to soil reaction.
force and thus, the highest draft force was observed for longitudinal velocity of 0.5 m/s at a speed ratio of 0.

For speed ratios of 1, 1.5 and 2, the tines of the rotating tine mechanism moved along different trajectories irrespective of longitudinal velocity (Fig. 5.4). The draft forces on the rotating tine mechanism for different speed ratios are due to longitudinal soil reaction forces on the tines and soil disturbance associated with the trajectories. Therefore, the decreasing trend of draft forces for speed ratios 1, 1.5 and 2 in this experiment can be found to match with that of predicted longitudinal force on two tines discussed in chapter 4 of this dissertation for the three speed ratios.

![Figure 5.4. Simulation results showing trajectories and soil disturbances of four tines of a rotating tine mechanism moving in a longitudinal direction and rotating anticlockwise. The top, middle and bottom plots are for ratios 1, 1.5 and 2 respectively.](image)

The research discussed in chapter 4 showed the tine becomes stationary at points in its trajectory for speed ratio 1, at which the longitudinal force on the tine also becomes zero. At speed ratio 1.5 and 2, longitudinal forces orient in the direction of tine velocity at points along
the loops generated in their trajectories. When longitudinal force is zero or orient in the direction of tine velocity, the overall draft force on the rotating tine mechanism is reduced for each longitudinal velocity. Thus, decreases in draft force with increasing speed ratios for each longitudinal velocity were probably due to decrease in longitudinal forces associated with trajectory and kinematics related to the speed ratios. The experimental result also showed the mean draft force was higher for higher levels of longitudinal velocity at given speed ratios. The results were consistent with the findings discussed in chapter 4 and were likely due to increases in tine velocity that contributed to increased inertial force component of the longitudinal soil force.

Similarly, the decreasing draft force for speed ratio 1, 1.5 and 2 could also be due to corresponding extent of soil disturbance occurring in the path of longitudinal travel (Fig. 5.4). Depending on the soil disturbed, a soil reaction force on a tine will decrease because of reduced shearing and inertial forces due to lower soil density in front of the tine. Moreover, the frictional force, which is typically small will be negligible compared to the shearing and inertial forces. The pattern of soil disturbance for the three speed ratios show the disturbance increases with speed ratios. This result implies that at higher speed ratios, the tines of the rotating tine mechanism predominantly operate in the soil with lowered resistance. As a result, the longitudinal force decreased and thus, decreasing the draft force with increasing speed ratios.

**Soil Reaction Torque**

Both longitudinal velocities and tool speed ratios had significant effects on torque at the 5% level, and there was significant interaction (Table 5.2). The mean torques at speed ratio of 0 was close to 0 N·m for all three longitudinal velocities. It was expected because the tine was not rotated for speed ratio 0. At each speed ratios 1 to 2, mean torque increased with increases in longitudinal velocity (Fig. 5.5). When rotated, the lowest mean torque of 3.32 N·m (standard
deviation of 0.18 N-m) was observed for the 0.09 m/s longitudinal velocity and ratio of 1. The highest mean torque was 4.94 N-m (standard deviation of 0.287 N-m), observed for the fastest longitudinal and rotational speed used in the experiment. Although the mean torques appear to increase with increasing speed ratios for most cases, there were trends of mean torques moving from speed ratio 1 to 1.5 and 1.5 to 2. The means of the torques increased as the ratio increased from 1 to 1.5 for all three levels of longitudinal velocity. However, the mean torque decreased for longitudinal velocity of 0.1 m/s, remained almost same for 0.29 m/s and increased for 0.5 m/s from speed ratio 1.5 to 2.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean of squares</th>
<th>F value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal velocity</td>
<td>2</td>
<td>3.27</td>
<td>1.63</td>
<td>27.044</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Speed ratio</td>
<td>3</td>
<td>171.33</td>
<td>57.11</td>
<td>945.251</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Longitudinal velocity*Speed</td>
<td>6</td>
<td>1.72</td>
<td>0.29</td>
<td>4.735</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

The torque on the rotating tine mechanism is the sum of torques placed on the mechanism by each individual tine. The torque on each tine along its trajectory can be approximated with tangential soil resistance force acting on the tine. The tangential force on a tine of the rotating tine mechanism, unlike longitudinal force, will always be positive, based on a previous study (chapter 4). Furthermore, tangential force increases with increasing tine velocity along the trajectory owing to higher inertial force. The velocity of a tine increased for higher speed ratios at any level of longitudinal velocity. Thus, the increase in mean torques with increasing speed ratios was due to larger tangential inertial forces acting on the tines. Tine velocities along its trajectory were also relatively higher for higher longitudinal velocity at any speed ratio. This
may have resulted the mean torques to be higher for higher levels of longitudinal velocity at each ratio.

![Figure 5.5. The interaction effect of longitudinal velocities and speed ratios on torque. Solid dots and error bars denote means and standard deviations respectively. The mean sharing same letters are not significantly different at p<0.05 using Tukey’s adjusted comparisons.](image)

The magnitudes of torques were also affected by extent of soil disturbance and interaction of the tine with disturbed soil for different speed ratios. Particularly the variation in trends of mean torques observed from speed ratio 1.5 to 2 for different longitudinal velocity could be predominantly caused by difference in soil disturbances for these speed ratios. At a speed ratio of 2, the extent of soil disturbance in an area of path traveled by the rotating tine mechanism was higher than the speed ratios of 1 and 1.5 (Fig. 5.4). Because of greater soil disturbances, the tangential force on the tine might have decreased for longitudinal velocity of 0.09 m/s, and thus, the mean torque decreased from speed ratio 1.5 to 2 (Fig. 5.5). However, for longitudinal velocities of 0.29 m/s and 0.5 m/s the resultant velocities were comparatively higher and thus, the tine for these cases registered larger tangential forces due to inertia despite having
higher soil disturbance. The resultant velocities for longitudinal velocity of 0.5 m/s was higher than for 0.29 m/s. Therefore, the increase in mean torque from speed ratio 1.5 to 2 was observed to be greater for the longitudinal velocity 0.5 m/s than for 0.29 m/s.

**Power**

The power to pull the rotating tine mechanism through the soil bin decreased with increasing speed ratios for all three longitudinal velocities used in the study (Fig. 5.6). The decreasing trend was expected due to reduced draft force with increasing speed ratios. The mean power requirement decreased by 59%, 54% and 56% for longitudinal velocities of 0.09 m/s, 0.29 m/s and 0.5 m/s respectively from non-rotational state corresponding to speed ratio 0 to rotational state of speed ratio 2. The approximate ranges of power required for draft of the mechanism was between 4 to 10 W for a longitudinal velocity of 0.09 m/s, 12 to 27 W at 0.29 m/s, and 28 W to 66 W at 0.5 m/s when operated between the speed ratios of 0 to 2.

![Figure 5.6](image)

**Figure 5.6.** Power requirement for draft of the rotating tine mechanism at different longitudinal velocities and speed ratios.
The power required for rotating the mechanism at desired test speeds increased with increasing speed ratios almost proportional to rotational test speeds (Fig. 5.7). The rate at which the power increased from speed ratio 0 to 2 was highest for longitudinal velocity of 0.5 m/s and lowest for 0.09 m/s. The highest power was a mean of 76 W with standard deviation of 4.3 W for speed ratio of 2 and longitudinal velocity of 0.5 m/s. The range of power required to rotate the mechanism to achieve speed ratios of 1 to 2 was lowest for longitudinal velocity of 0.09 m/s and was roughly between 5 to 13 W.

![Figure 5.7. Power required to achieve different rotational speed of the rotating tine mechanism at different longitudinal velocities and speed ratios.](image)

The total power for draft and rotation of the rotating tine mechanism increased with increasing speed ratios (Fig. 5.8). Despite the steep rate of increase of power to rotate the mechanism, the rate of total power for operating the mechanism did not increase correspondingly at higher speed ratios because lower power was required for draft of the mechanism at higher speed ratios. The range of total power was lowest for longitudinal velocity of 0.09 m/s and was
approximately between 9 W to 16 W. While the highest range was found to be roughly between 60 W to 110 W for longitudinal velocity of 0.5 m/s. The range of total power for longitudinal velocity of 0.29 m/s was around 25 W to 51 W.

![Figure 5.8. Total power requirement for operating the rotating tine mechanism at different longitudinal velocities and speed ratios in the experiment.](image)

Operating the rotating tine mechanism at 0.09 m/s seem results in low requirements; however, for timely mechanical weeding operations, this speed might not be favorable for field capacity. The brush weeder and weeder mechanism for ECO-weeder with similar to rotating tine mechanisms have been reported to move at forward travelling speeds greater than 0.22 m/s for intra-row mechanical weeding operations (Ahmad et al., 2014). For reduced draft requirements of the rotating tine mechanism travelling at higher speeds, adjusting rotational speeds seems to be the preferred operational setting. The reduced draft requirement of the mechanism at higher speed ratios can make actuation of the mechanism easier to control for active intra-row weed control. Moreover, rotational speed associated with higher speed ratios can enable the mechanism to potentially damage higher proportion of weed plants by uprooting, cutting or
burying (Kshetri et al., 2019). However, the power for rotation can increase rapidly with increasing speed ratios or rotational speeds as shown in figure 5.7. Therefore, selection of linear and rotational speeds for the weeding operation should be optimized to increase weeding performance without exceeding power source limitations. Since higher speed ratios are effective for weed damage, linear speed may have to be reduced so that the mechanism can be operated at lower rotational speed without requiring considerable amount of power.

The measured draft force and torque and calculated power show that linear and rotational velocities of the rotating tine mechanism can be adjusted to different settings to achieve desired efficacy and efficiency for mechanical intra-row weeding. It is possible to reduce soil resistance forces, torques and power on the mechanism by changing tine design, using higher number of tines, and mounting the tines closer to the center of the rotating tine mechanism’s disc. These modifications can increase capacity of the mechanism to operate at higher linear and rotational velocities in the soil. As a result, there could be higher flexibility in selection of appropriate linear and rotational velocities for effective weed control.

**Conclusions**

From this research, we can conclude:

- **Horizontal draft force decreases whereas torque increases with increasing speed ratios over the experimental range of rotating tine mechanism longitudinal velocities in loam soil.** At each speed ratio, the draft force and torque increased with increasing longitudinal velocity. The effects of longitudinal velocity and speed ratio on draft force and torque on the mechanism were non-linear in nature.

- **Total power also increased with increasing speed ratios for all three longitudinal velocities.**
References


ASAE Standards, 46 Ed. (1999a). S313.3. Soil cone penetrometer. ASAE, St Joseph, MI.

ASAE Standards, 46 ED (1999b). EP542. Procedures for using and reporting data obtained with the soil cone penetrometer. ASAE, St Joseph, MI.


CHAPTER 6. GENERAL CONCLUSIONS

In this research, interaction between soil and tine was studied for a rotating tine mechanism associated with a mechanical intra-row weeder, designed for vegetable crop production. The mechanism consisted of a disk with cylindrical vertical tines that engaged the soil during the weeding operation. Two aspects of soil-tine interaction, soil disturbance and forces were investigated to determine weeder performance. Performance was studied at different tine settings while maintaining fixed soil properties and conditions. Experiments for each research objective were conducted in soil bins under controlled environment maintaining constant soil conditions.

The first objective of the research was to study the soil-tool using simulated weeds to investigate weeding efficacy at different settings. The results showed the width of soil disturbance due to single narrow tine increased with increases in tine diameter and working soil depth. However, there was no significant evidence that the travel speeds affected the width of soil disturbance. The single tine experiment also showed that potential weeding rate increased with increasing diameter, soil depths and travel speeds. For the rotating tine mechanism, increasing working soil depths and rotational speeds increased potential weeding rate of the mechanism. A simulation estimated the effective area of soil disturbance for the rotating tine mechanism, and the estimates had trends similar to the experimental potential weeding rate for different settings. This result suggested simulation can be used to estimate weeding efficacy of the weeder mechanisms.

The second research project focused on developing and evaluating models for estimating soil forces on a vertical tine of a rotating tine mechanism operating at different linear and rotational velocities. Models were developed for longitudinal and tangential soil forces which
contributed to horizontal draft force and torque on the tine, respectively. The models were based on position and velocity of the tine along its trajectory at different settings of longitudinal velocities and speed ratios. Model parameters $K_S$ and $K_I$ captured shearing and inertial effects on the forces due to soil-tine interactions and were evaluated empirically. These parameters were found to vary for different experimental settings. $K_S$ decreased with increasing speed ratios corresponding to increased soil disturbance. While the trend for $K_I$ was not so obvious, possibly because its value was dependent on combined effects of soil disturbance and tine velocities, which were complex in nature. Forces predicted using the model for two tines matched with experimental results showing draft force decreases while torque increases with increasing speed ratios. However, the magnitudes of predicted forces were higher than those of measured forces because the models did not include the effects of previously disturbed soil which would reduce overall forces on a tine.

The third objective of the research was to investigate effects of longitudinal and rotational velocities on horizontal (draft) force, torque and power on the rotating tine mechanism operating in the soil. Experiments conducted using three levels of longitudinal velocity (0.09 m/s, 0.29 m/s, 0.5 m/s) and four levels of speed ratio (0, 1, 1.5, 2) showed that, in general, draft forces decreased while torques increased with increasing speed ratios for different longitudinal velocities. These relationships were found to be non-linear and were explainable using the previously-developed model. The power decreased to pull the mechanism through the soil while the rotational power increased when speed ratios were increased. The total power for operating the mechanism increased with increasing speed ratios. From the research it can be inferred that by adjusting linear and rotational velocities, weeding performance of the mechanism can be optimized while operating within the power limitation of the power source.
The soil and tine interaction study conducted in the research provide valuable insight on how higher weeding performance can be achieved with the rotating tine mechanism. Higher mechanism rotational speed will potentially damage more weeds through soil disturbance. However, if the linear traveling speed of the mechanism is increased while keeping rotational speed fixed, the speed ratio will decrease resulting in a pattern of soil disturbance that can damage a lower proportion of weeds during the operation. Therefore, proper settings of linear and rotational speeds should be selected for effective weed control. Furthermore, generally higher travel speeds are preferable for timely mechanical weeding application. At higher travelling speeds, rotational speeds of the mechanism need to be increased to achieve higher speed ratios that are conducive for effective weed damage. However, at higher levels of linear and rotational speeds, the torque and power requirements for the operation can become large, potentially beyond the capacities of the actuators employed for the operation. The study shows settings for the two speeds could be optimized to keep power requirement for effective weeding operation below the limitation of the available power sources. Higher speed ratios can also lower draft force required for controlling actuation of the mechanism in and out of the crop rows for active intra-row weed control. This knowledge can help make better judgement on sizing of power sources to meet energy requirements at desired operational settings. The models developed for predicting forces on the tines of the mechanism could be used to approximate possible draft, torque and power requirement for different linear and rotational settings.

Limitations and Suggestions for Future Work

The research studied interaction between soil and a rotating tine mechanism to explore the effects of different operational parameters and settings on soil disturbance and soil forces on the mechanism. The study primarily focused on intra-row weeding and was based on the selection of fixed parameters and settings of a vertically rotating weeding tine mechanism
conducted under controlled indoor conditions. The investigation of soil and tool interaction primarily focusing on weed control can be valuable for mechanical weeding application; however, this approach cannot be found discussed in the literature. Moreover, the research investigated the use of vertically rotating tine mechanism for field cultivation, an approach to tilling soil that has not been explored extensively.

Based on the experience gained from this research, there are several possible avenues for research in the future. The experiments for this research were conducted with fixed soil properties, which may vary in the field. Therefore, outcomes of the research may need to be validated or explored with different soil properties and conditions at different tool settings. The soil resistance forces on the rotating tine mechanism that contribute to draft force and torque can be studied for higher travel speeds and speed ratios. The travel speeds used in the research were slower than the travel speeds needed field capacities for practical implementation. Similarly, soil disturbance and soil forces for the rotating tine mechanism can be studied for different tine designs and number of tines.

The rotating tine mechanism was intended to actively maneuver between the crops in a row. Since soil resistance can affect controlled actuation of the mechanism, soil forces opposing active mechanism motion control should be studied for different travel speeds and rotational speeds. Further, the soil disturbance for weeding during lateral motion may be impacted by travel speeds, rotational speeds and lateral actuation. Therefore, weeding performance can be studied for the rotating tine mechanism for different travel speeds, rotational speeds and trajectory settings that require lateral motion.
REFERENCES


USDA ERS. (Feb 05). *Corn and soybeans accounted for over 40 percent of all U.S. crop receipts in 2018*. http://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=76946


**APPENDIX . MEASURED AND MODELED FORCES COMPARISON**

Figure A1. Comparison between the measured and modeled longitudinal and tangential forces for longitudinal velocity of 0.29 m/s and speed ratios of 1 (top row), 1.5 (middle row) and 2 (bottom row).
Figure A2. Comparison between the measured and modeled longitudinal and tangential forces for longitudinal velocity of 0.50 m/s and speed ratios of 1 (top row), 1.5 (middle row) and 2 (bottom row).